Structure of Mg Isotope Studied by β-Decay Spectroscopy of Spin-Polarized Na Isotopes - Shape Coexistence in ^{30}Mg -

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in collaboration with
KEK, TRIUMF, Univ. Paris and IPN Orsay

study for the nuclear structure of neutron-rich nuclei in the vicinity of **island of inversion**

^{28}Mg, ^{29}Mg, **^{30}Mg**

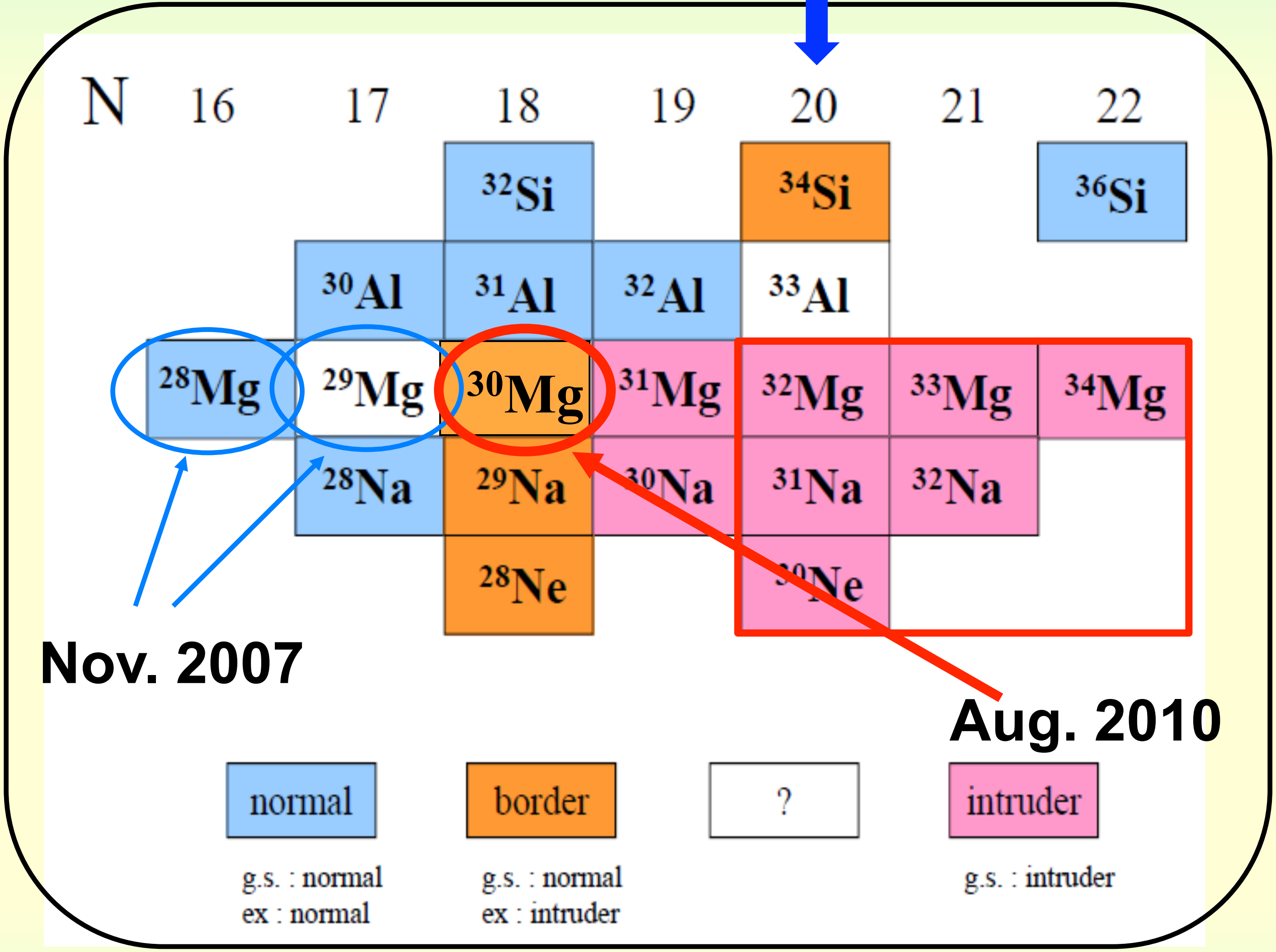
shell evolution as a function of neutron number

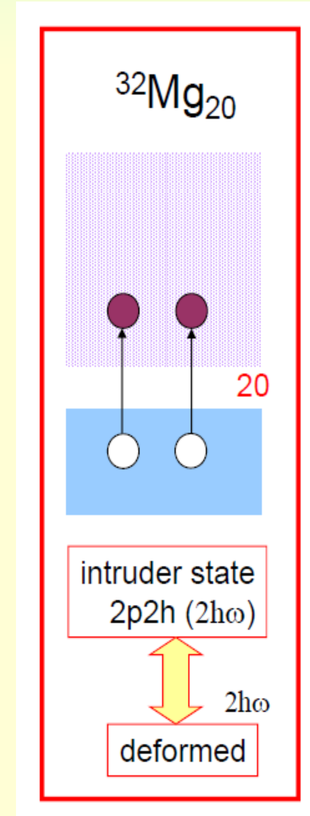
new method by the β decay of the spin-polarized Na isotopes can determine the spin-parity of levels.

1. introduction

Island of inversion

magic number?





E.K. Warburton et al.,
Phys. Rev. C 41 (1990) 1147

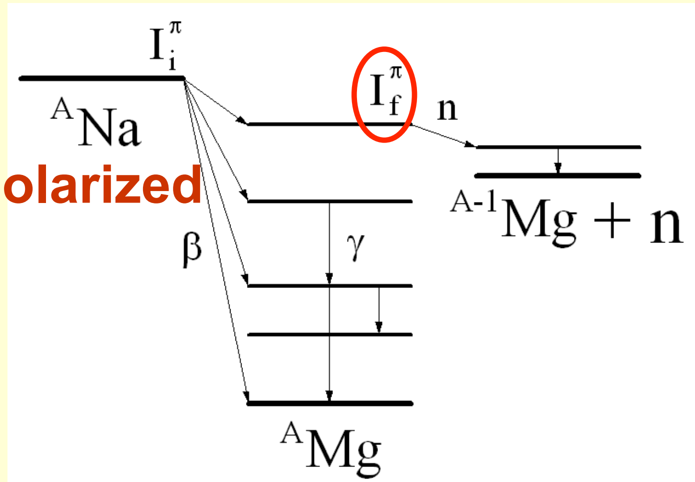
Which level has the intruder configuration?
How does shell structure evolve with *N*?

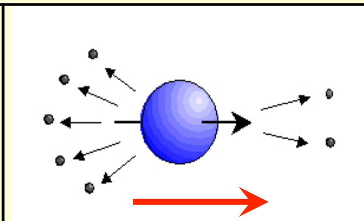
2. new method to assign spin-parity using spin-polarized beam

β-decay spectroscopy using spin-polarized beam

very effective method to assign spin-parity of daughter states

polarized





polarization

β-decay angular distribution

$$W(\theta) \simeq 1 + AP\cos\theta$$

allowed transition

A: asymmetry parameter of allowed β-decay

P: polarization of the parent nucleus

initial final

$$A(I_i, I_f) \begin{cases} = \dfrac{I_i}{I_i+1} & (\text{for } I_f = I_i + 1) \\ \simeq \dfrac{-1}{I_i+1} & (\text{for } I_f = I_i) \\ = -1 & (\text{for } I_f = I_i - 1) \end{cases}$$

assume pure GT

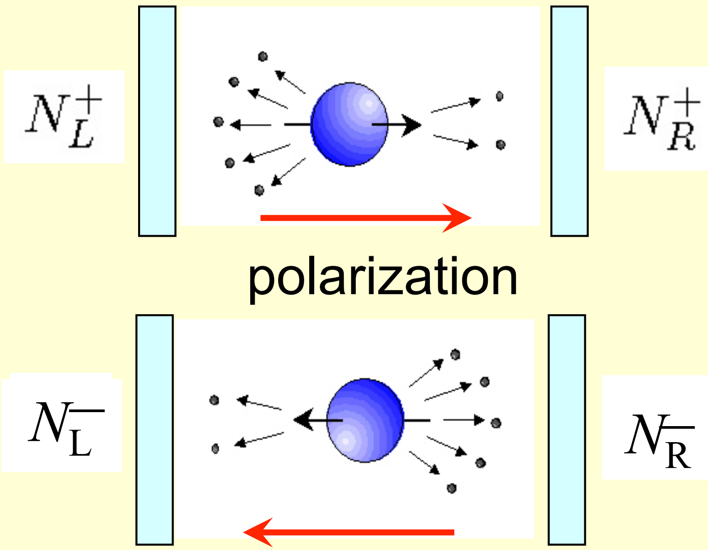
A takes very different values depending on the final state spin.

	I_i^π (Na)	I_f^π (Mg)	$A(I_i, I_f)$
^{28}Na	1^+	2^+	$+0.5$
		1^+	-0.5
		0^+	-1.0
^{29,31}Na	$3/2^+$	$5/2^+$	$+0.6$
		$3/2^+$	-0.4
		$1/2^+$	-1.0
^{30}Na	2^+	3^+	$+0.67$
		2^+	-0.33
		1^+	-1.0

2. new method to assign spin-parity using spin-polarized beam

(1) how to deduce *AP* value

β-ray detection



$$W(\theta) \simeq 1 + AP\cos\theta$$

$$N_R^+ = \epsilon_R \times (1 + AP) \text{ x}N_0$$
$$N_L^+ = \epsilon_L \times (1 - AP) \text{ x}N_0$$

$$N_R^- = \epsilon_R \times (1 - AP) \text{ x}N_0$$
$$N_L^- = \epsilon_L \times (1 + AP) \text{ x}N_0$$

ε: detection efficiency

spin reversed

$$AP = \frac{\sqrt{R} - 1}{\sqrt{R} + 1} \quad \left(R = \frac{N_R^+}{N_L^+} \Big/ \frac{N_R^-}{N_L^-} \right)$$

free from instrumental asymmetry

(2) how to determine spin

P can be evaluated from ***AP*** value for a transition to the known spin state.

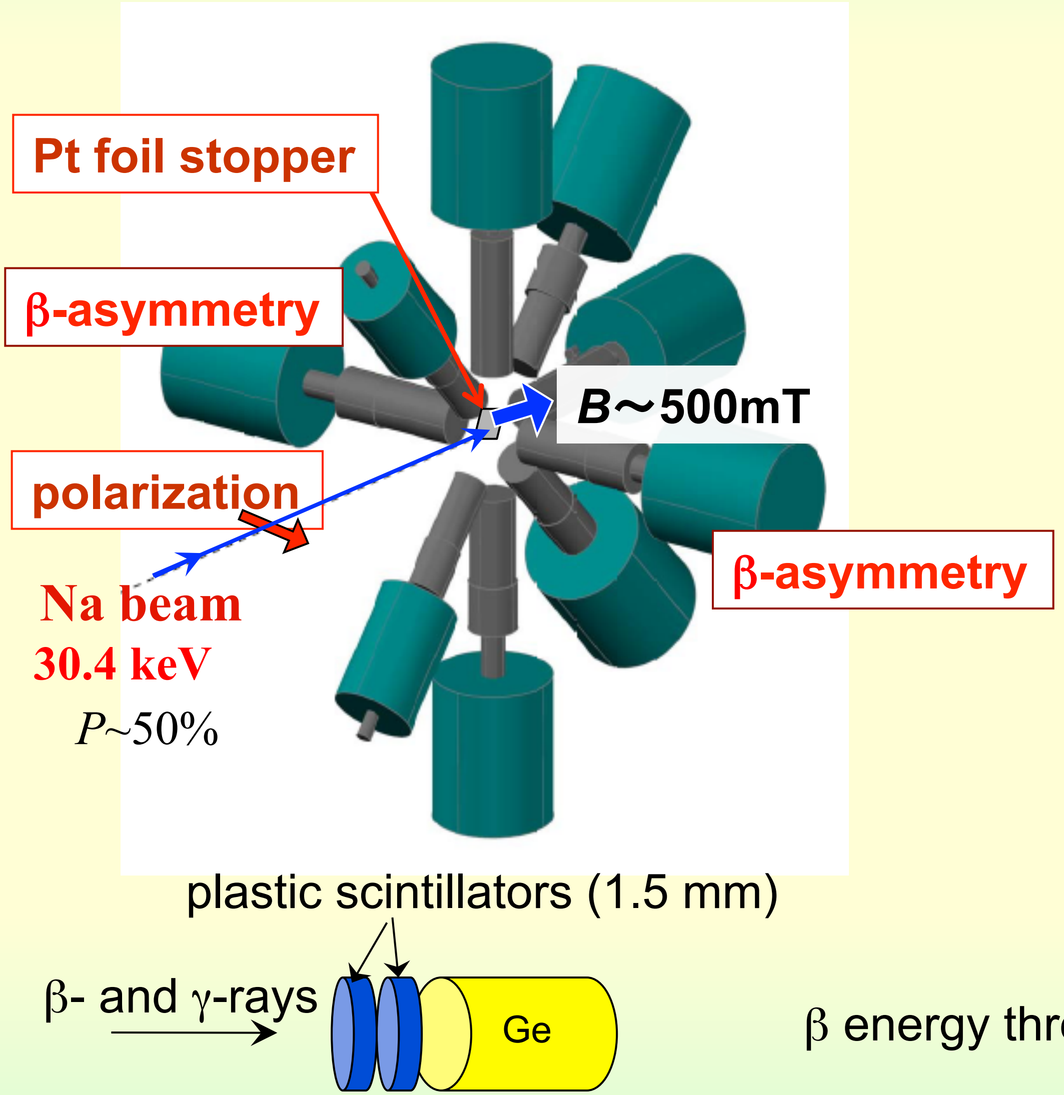
A → spin assignment

3. experiment

^{30}Na decay at TRIUMF

9 HPGe detectors + plastic scintillator telescopes

β-asymmetry: β−γ, β−γ−γ, γ−γ



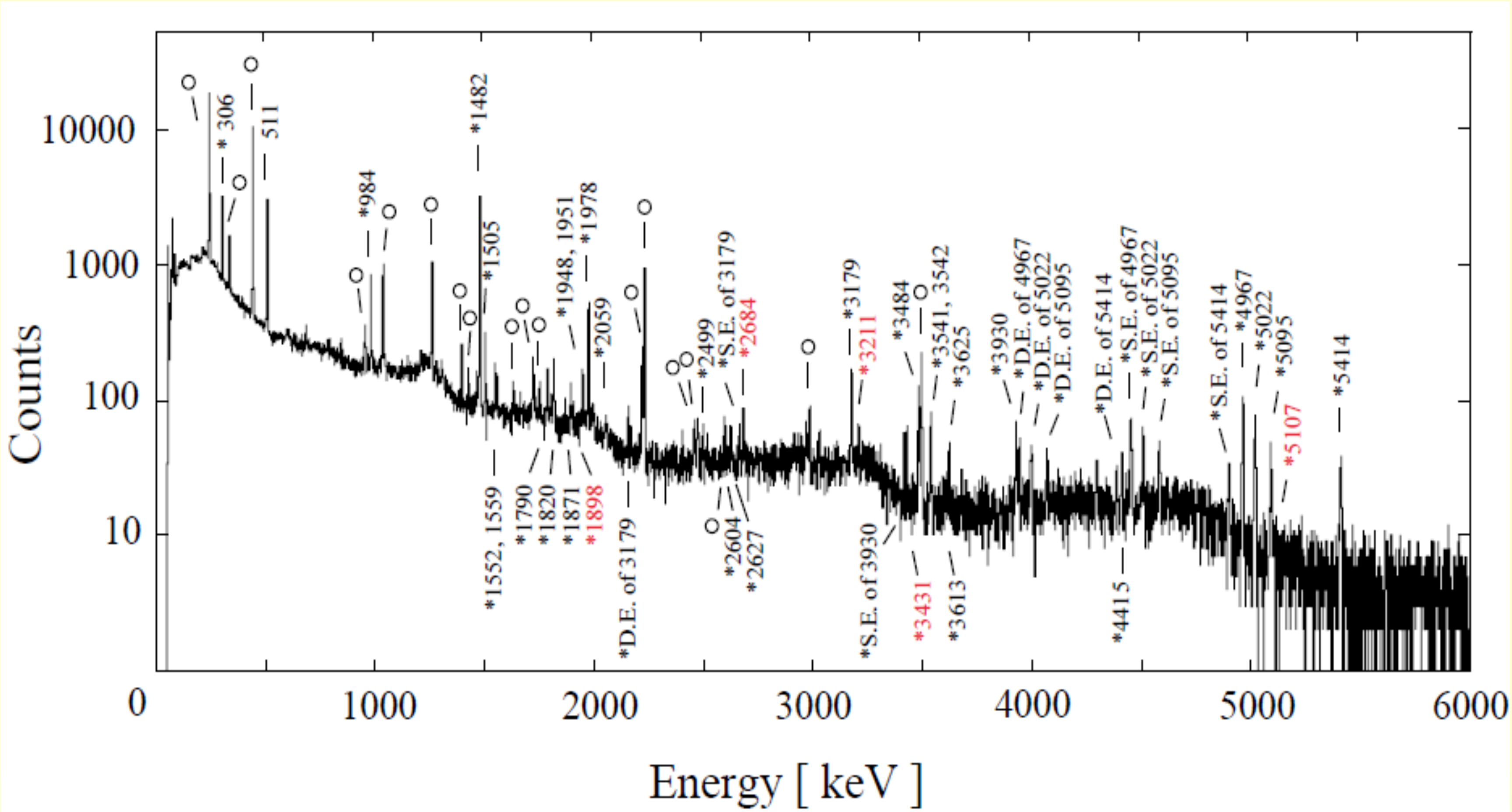
total efficiency
2.5% @1333keV

28Na and 29Na in Nov. 2007
30Na in Aug. 2010

β energy threshold: eliminates Al contaminants from trigger

β energy : assigns β-decay branch

4. results
(1) γ-ray spectrum of β-γ coincidence mode



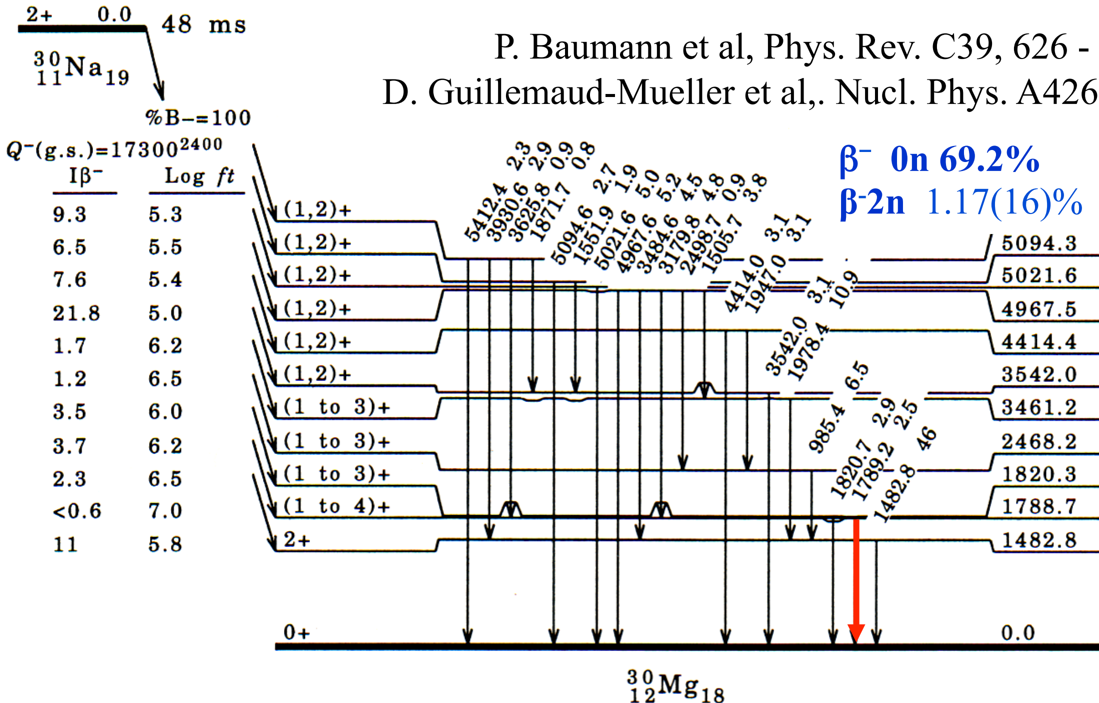
peaks with energy value: γ-transitions in ^{30}Mg (red: newly found)

O: background

^{30}Mg

NNDC
P. Baumann et al, Phys. Rev. C39, 626 - 635 (1989)
D. Guillemaud-Mueller et al,. Nucl. Phys. A426, 37 (1984)

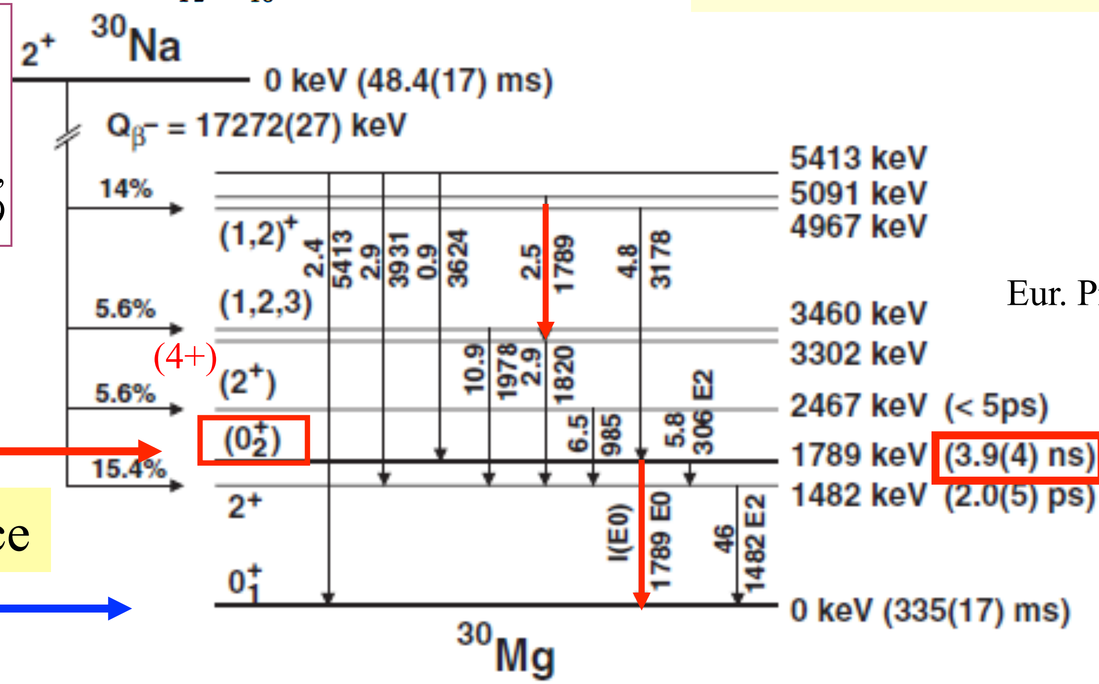
β^- **0n 69.2%** β^-**1n** 30(4)%
β^-**2n** 1.17(16)% $\beta^-\alpha$ 5.5E-5(20)%



Reported level schemes before our experiment

(4$^+$) at 3302 keV
H(^{32}Mg,^{30}Mgγ)X
S. Takeuchi et a;.,
Phys. Rev. C 79 (2009) 054319

W. Schwerdtfeger et al.,
Phys. Rev. Lett. 103,
(2009) 012501



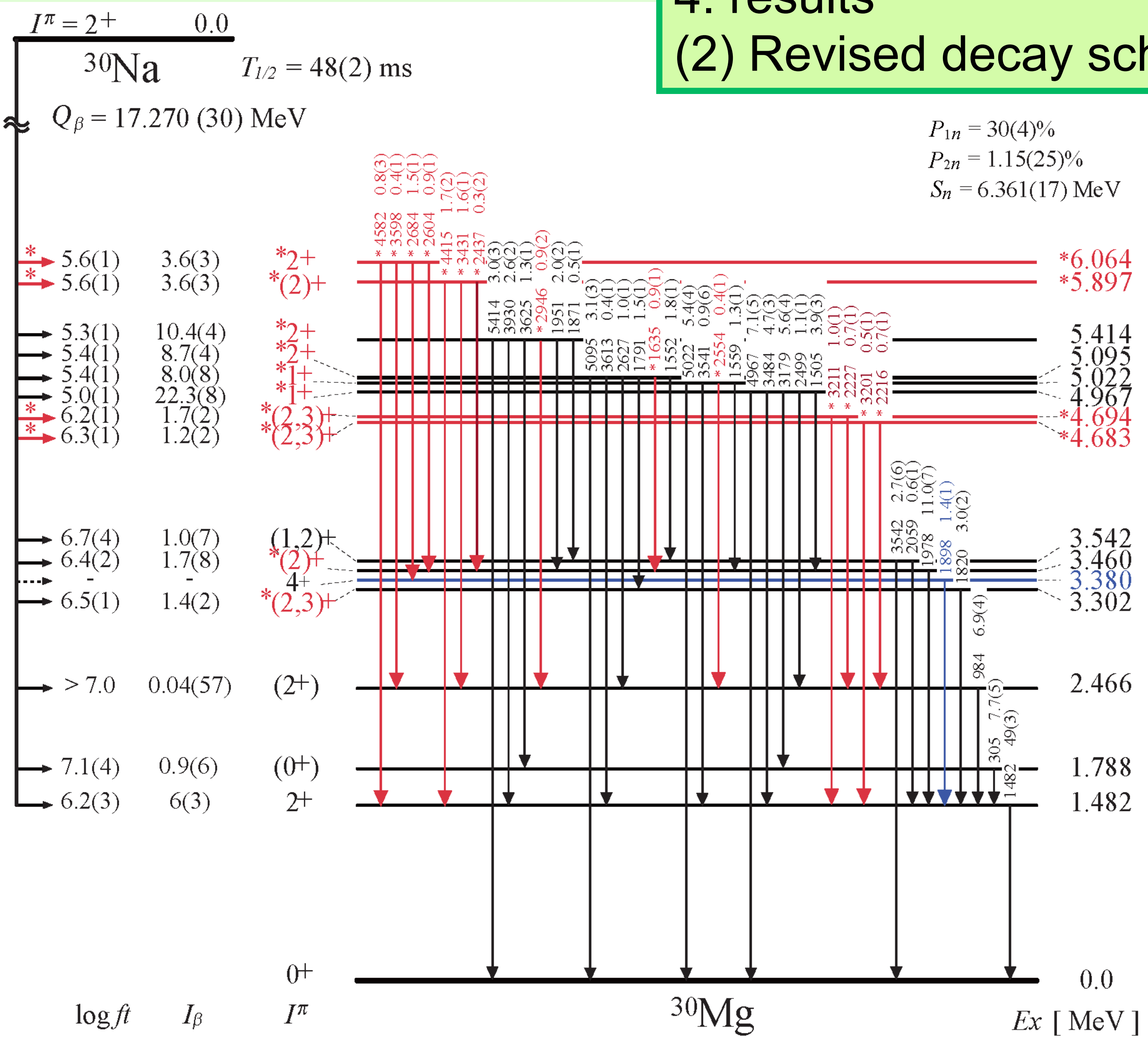
H. Mach et al.,
Eur. Pnys. J. A 25, s01
(2005) 105

deformed 0$^+$

shape coexistence

normal 0$^+$

4. results
(2) Revised decay scheme of ^{30}Na

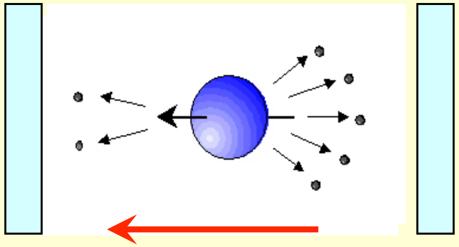


New findings are in red.

14 γ rays &
4 energy levels
Spins & parities of 10 levels

4. results (2) polarization and spin
(2-1) deduced AP values for 2 levels

N_L^+

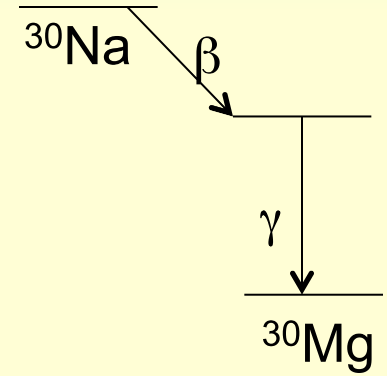


N_R^+

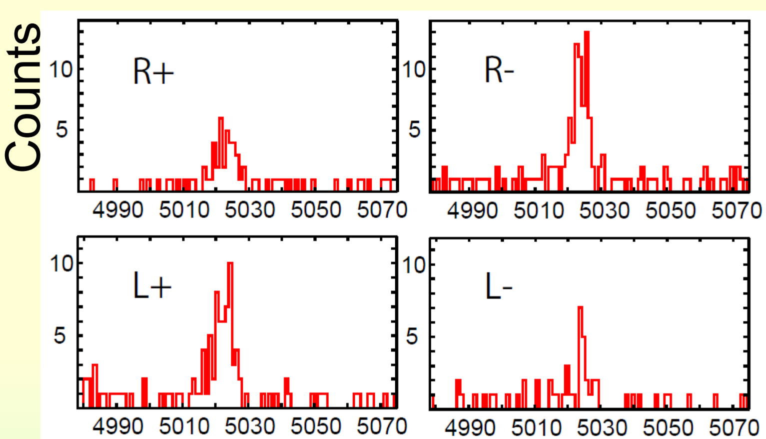
polarization

$$W(\theta) \simeq 1 + AP\cos\theta$$

$$AP = \frac{\sqrt{R}-1}{\sqrt{R}+1} \qquad \left(R = \frac{N_L^{\ +}}{N_R^{\ +}} \bigg/ \frac{N_L^{\ -}}{N_R^{\ -}}\right)$$



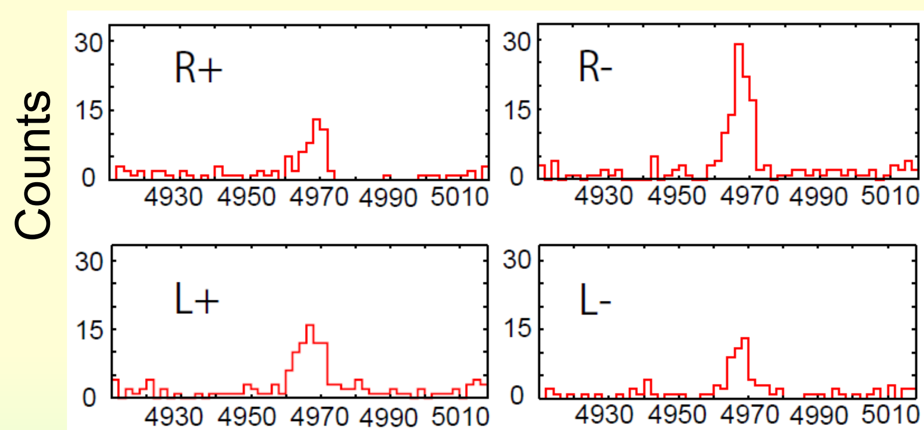
5022 keV γ ray depopulating the 5.022MeV level



Energy [keV]

$$A_{5.022}P = 0.38 \pm 0.06$$

4967 keV γ ray depopulating the 4.967MeV level



Energy [keV]

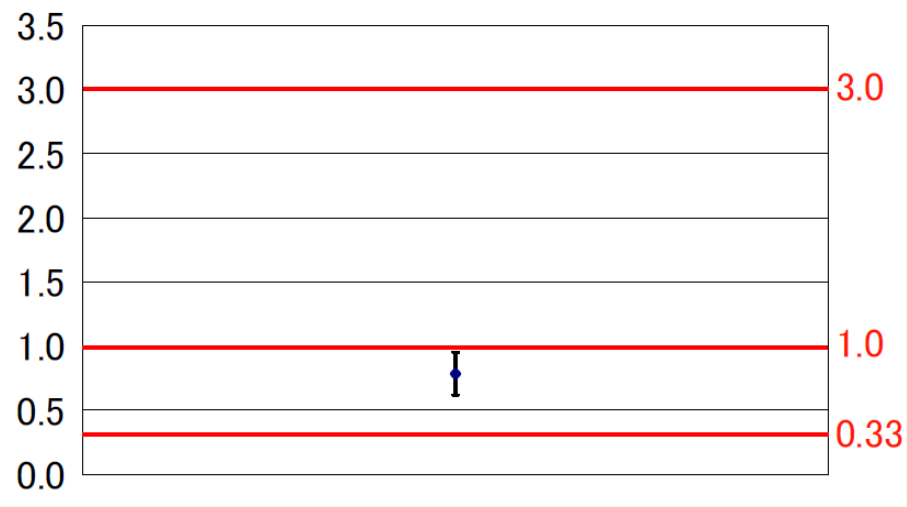
$$A_{4.967}P = 0.29 \pm 0.04$$

4. results (2) polarization and spin
(2-2) spin assignment from the deduced AP value

***AP* ratio** $$\frac{A_{4.967}P}{A_{5.022}P} = \frac{A_{4.967}}{A_{5.022}} = 0.76 \pm 0.16$$

Spins & parities of these 2 levels were reported to be (1, 2) $^+$.

I^{π}	A
1 $^+$	**-0.33**
2 $^+$	**-1.0**



$$\frac{A_{2+}}{A_{1+}} = 3$$

$$\frac{A_{2+}}{A_{2+}} \; or \; \frac{A_{1+}}{A_{1+}} = 1$$

$$\frac{A_{1+}}{A_{2+}} = 0.33$$

A/A : 4 patterns

$$\frac{I^{\pi}{}_{4.967}}{I^{\pi}{}_{5.022}} = \frac{1^+}{1^+} \; or \; \frac{2^+}{2^+}$$

Which is appropriate ?

4. results (2) polarization and spin
(2-3) deduced polarization P and determined spin

Which is appropriate ?

$$\frac{I^{\pi}{}_{4.967}}{I^{\pi}{}_{5.022}} = \frac{1^+}{1^+} \; or \; \frac{2^+}{2^+}$$

Evaluation of spins & parities by calculating Polarization *P*

$$A_{5.022}P = 0.38 \pm 0.06$$

$$A_{4.967}P = 0.29 \pm 0.04$$

$$A_{5.022} = -0.33$$

$$A_{4.967} = -0.33$$

$$\left(\frac{I^{\pi}{}_{4.967}}{I^{\pi}{}_{5.022}} = \frac{2^+}{2^+}\right)$$

$$\cancel{P = 1.14 \pm 0.17}$$

$$\cancel{P = 0.86 \pm 0.11}$$

Too high !

$$\left(\frac{I^{\pi}{}_{4.967}}{I^{\pi}{}_{5.022}} = \frac{1^+}{1^+}\right)$$

$$A_{5.022} = -1.0$$

$$A_{4.967} = -1.0$$

$$P = 0.38 \pm 0.06$$

$$P = 0.29 \pm 0.04$$

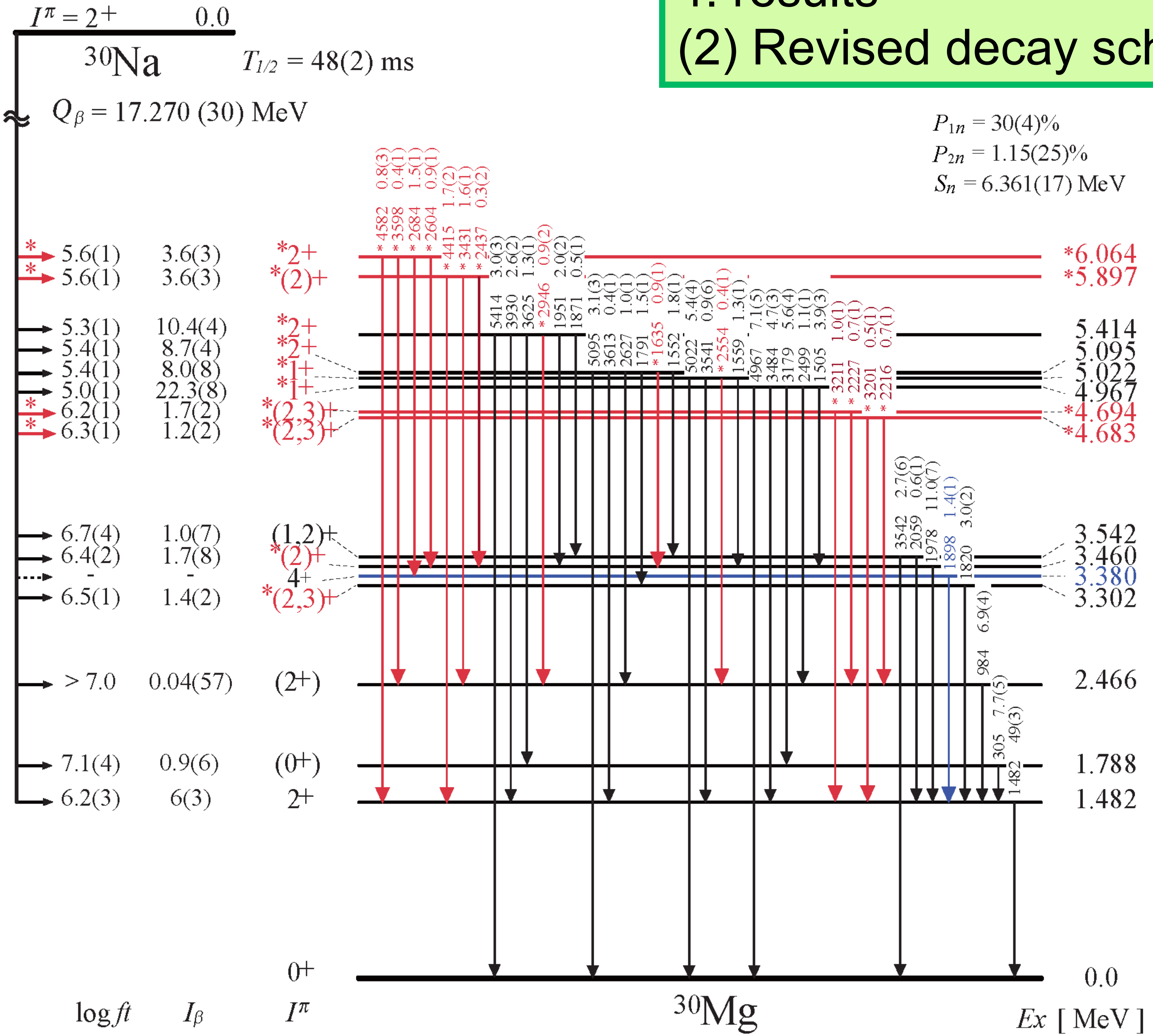
Polarization of ^{30}Na

32 ± 3 %

Spins and Parities of the 4.967, 5.022 MeV levels

$$I^{\pi}{}_{4.967} = 1^+, I^{\pi}{}_{5.022} = 1^+$$

4. results
(2) Revised decay scheme of ^{30}Na



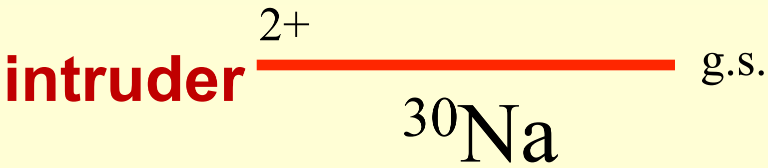
New findings are in red.

14 γ rays &
4 energy levels
Spins & parities of 10 levels

We can confirm I^π for 5 levels.

5. discussion 1

(1) candidate of the intruder states : level at 1.788 MeV



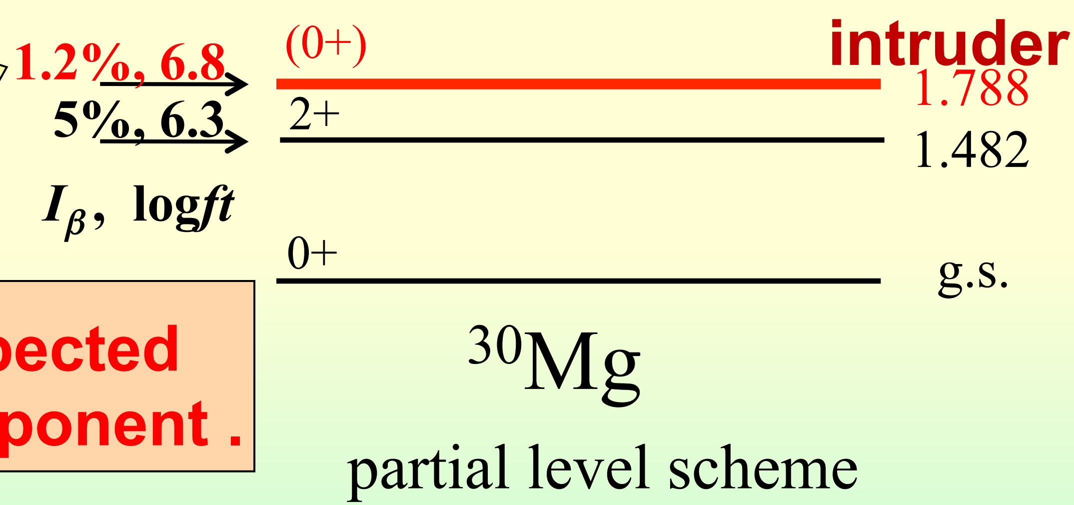
1.788 MeV (0^+) :

large β-decay intensity,

even though

secondary forbidden

previously reported to be I_β ~ 0 %

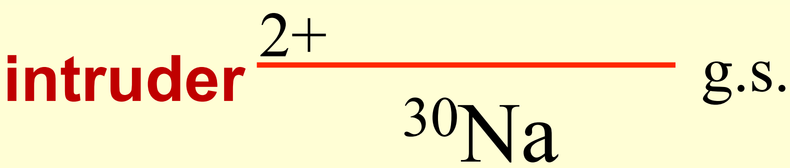


Level at 1.788 MeV is expected to have the intruder component .

5. discussion 1

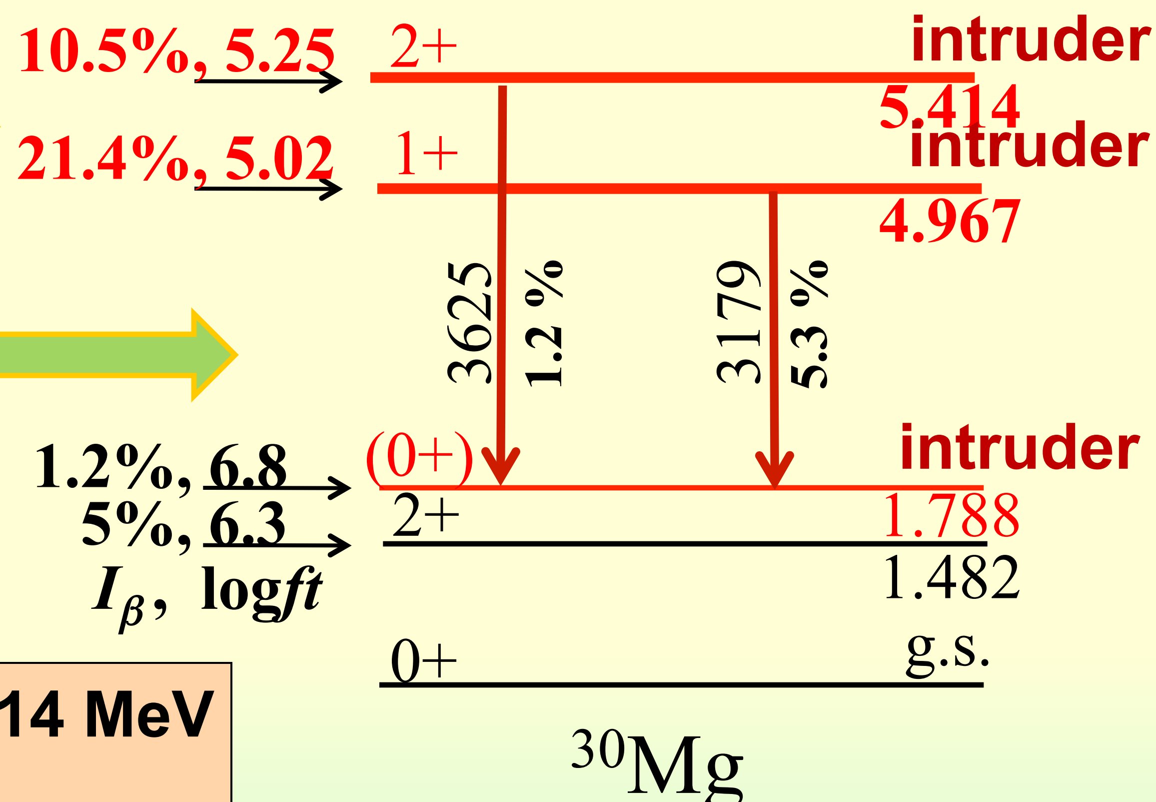
(2) candidate of the intruder states :

levels at 4.967 and 5.414 MeV



Large branching ratio of β decay

Level at 1.788 MeV is populated by γ rays from these 2 levels.



partial level scheme

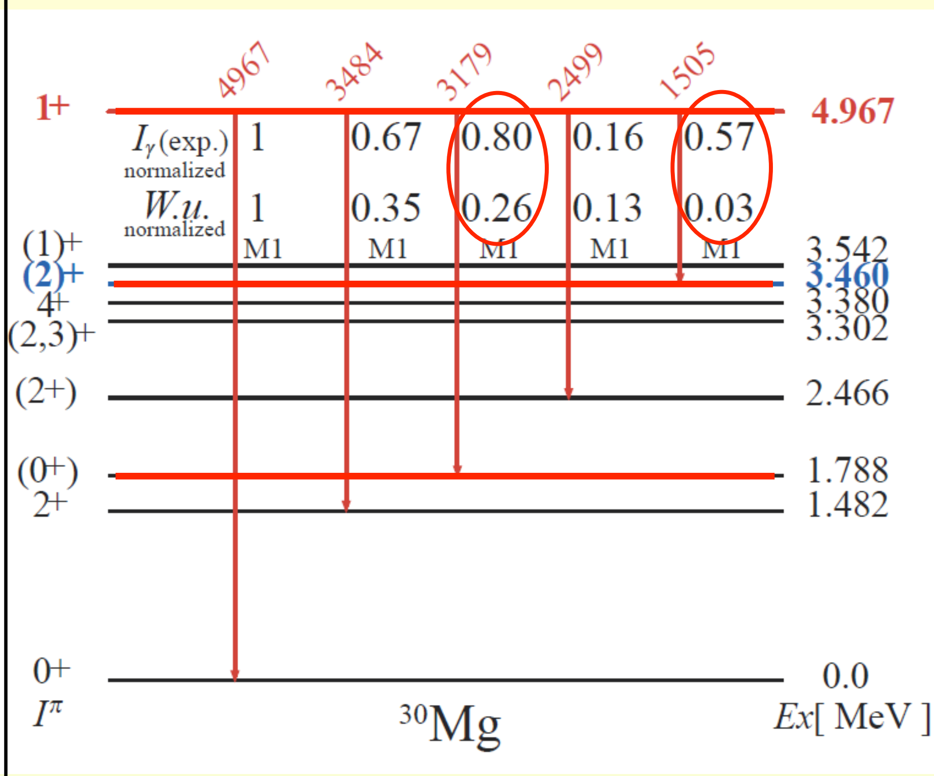
Levels at 4.967 and 5.414 MeV are expected to have the intruder component .

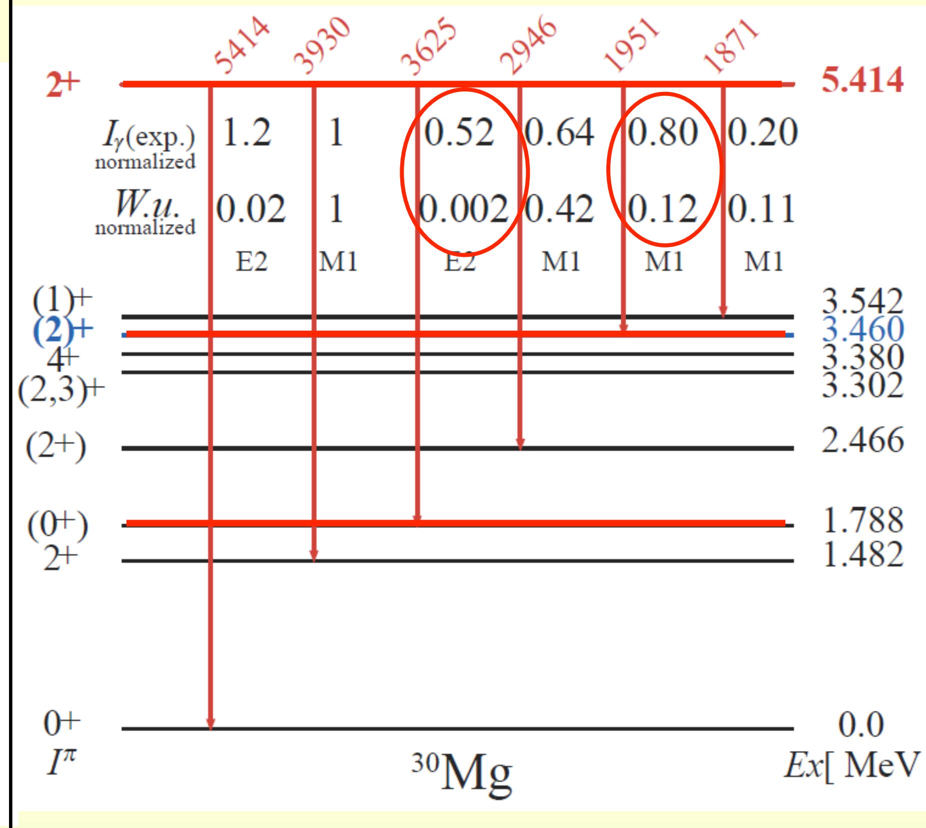
5. discussion 1

(3) candidate of the intruder states : level at 3.460 MeV

Branching ratios of γ-rays

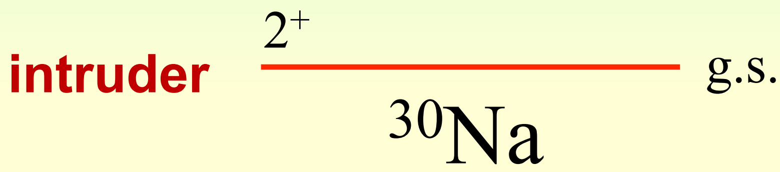
Enhancement compared with Weisskopf estimate





Levels at 5.414 MeV[2^+], 4.967 MeV[1^+], 3.460 MeV[(2^+)] and 1.788 MeV[(0^+)] are expected to have mainly intruder component.

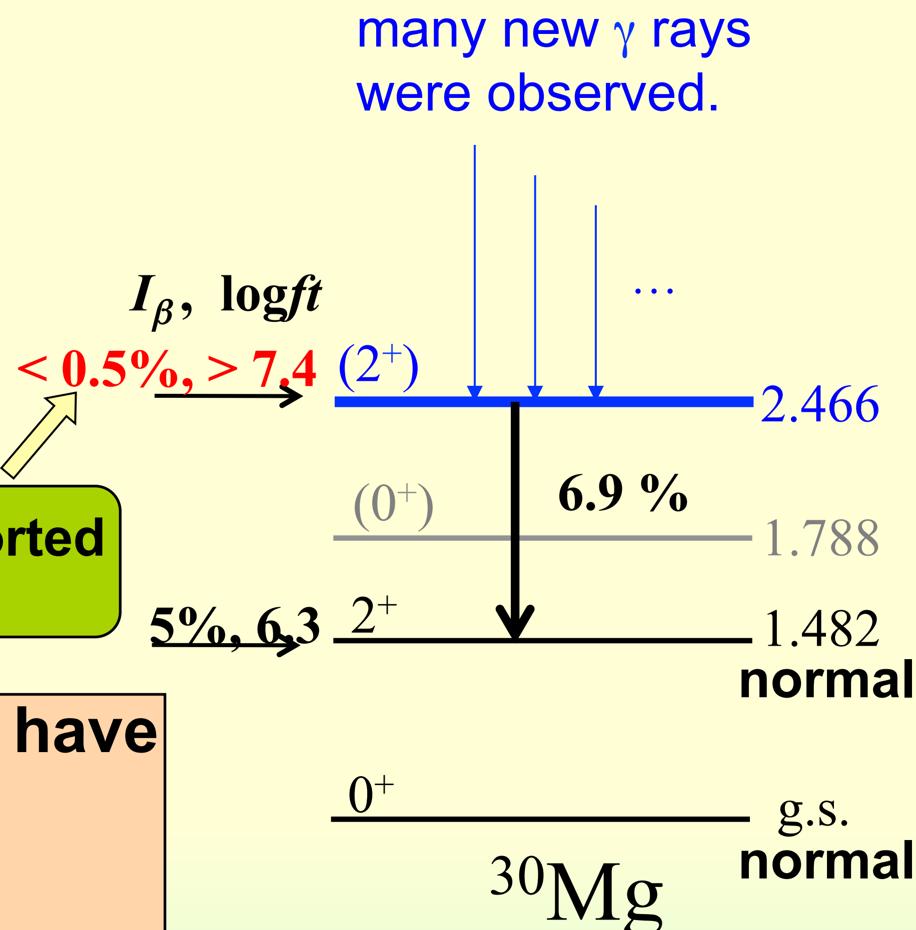
5. discussion 1
(4) What kind of level at 2.466 MeV ?



To the level at 2.466 MeV, no or very small β-decay branching ratio.

2^+ in ^{30}Na ⇨ 2^+ in ^{30}Mg

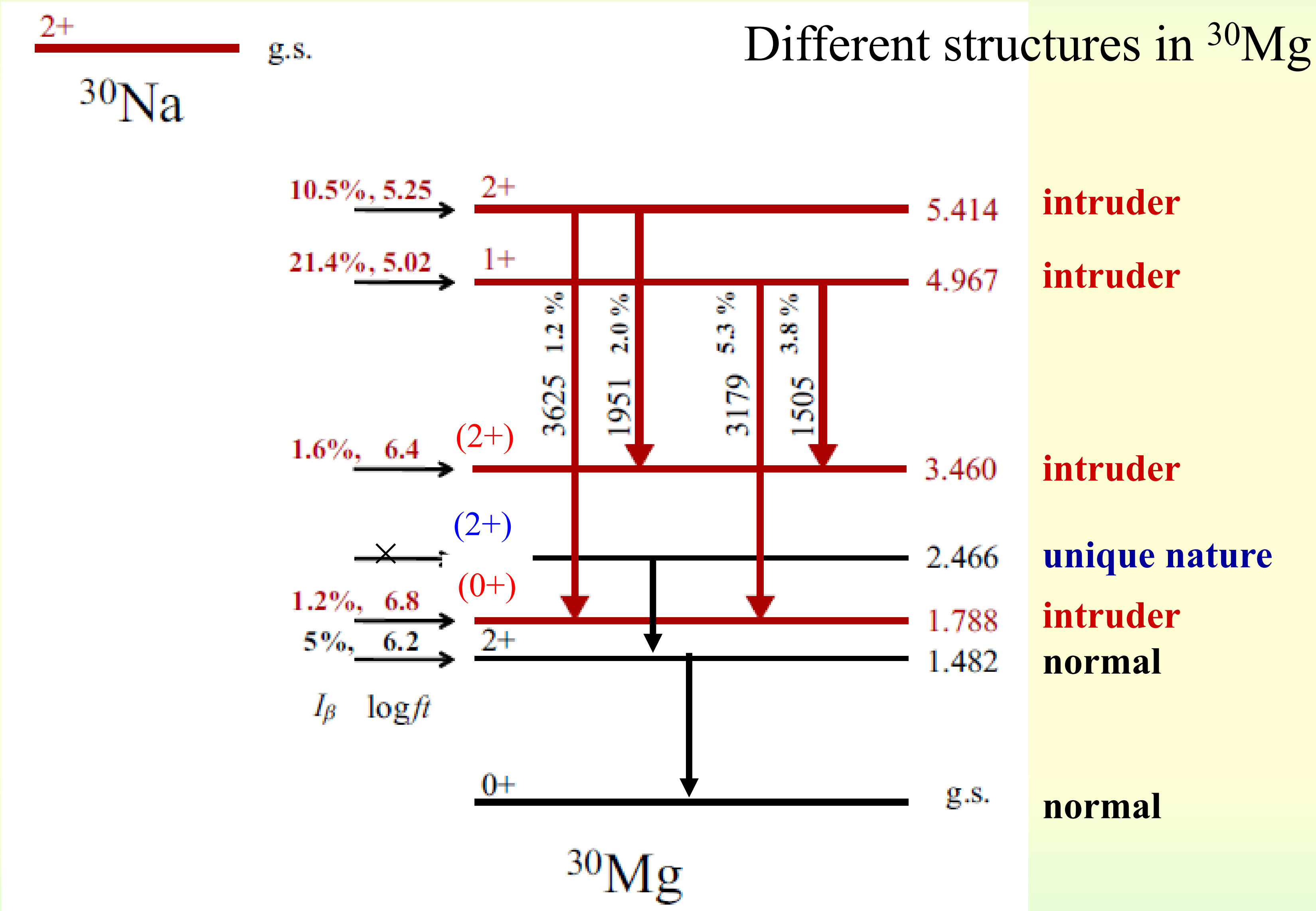
previously reported to be I_β ~6 %



partial level scheme

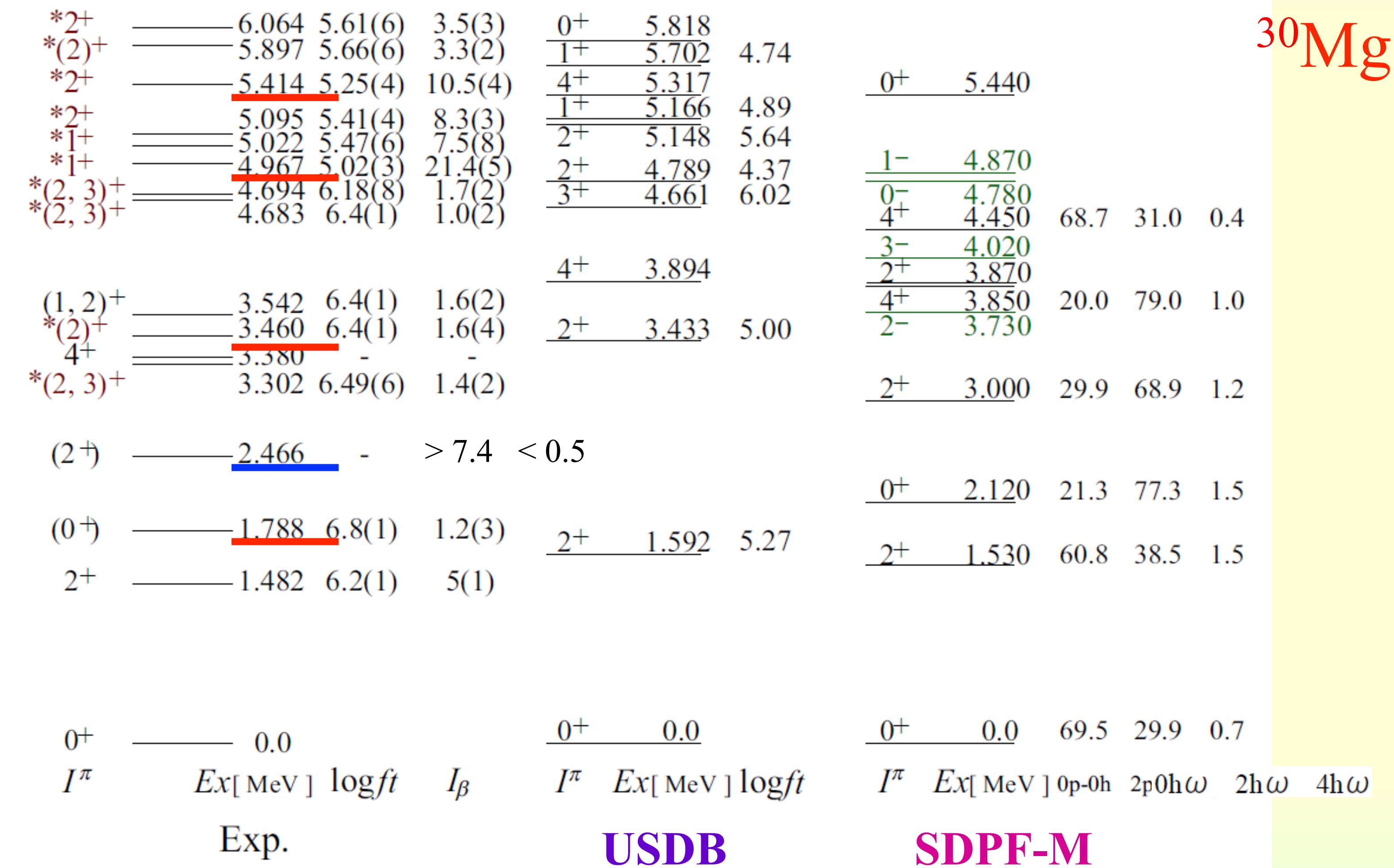
Level at 2.466 MeV (2_2^+) maybe have different nuclear structure from the levels at 2^+ in ^{30}Na(intruder) and at 1.482 MeV 2_1^+ in ^{30}Mg (nomal).

5. discussion 1 (5) summary



partial level scheme

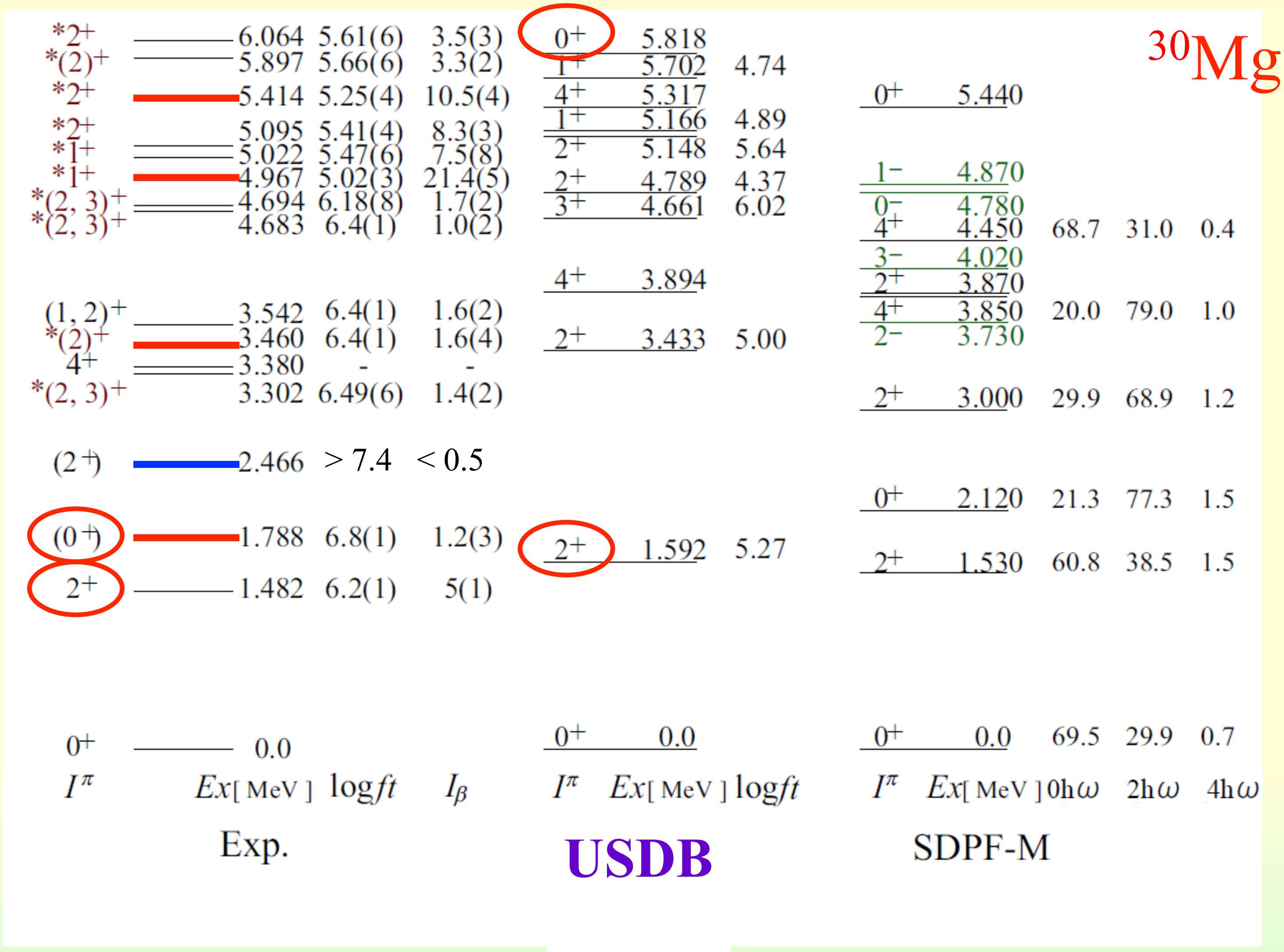
5. discussion 2 :
Comparison between experimental results and calculation
(1) Shell model calculation (USDB and SDPF-M)



by NuShell
Present work

by Monte Carlo Shell Model (MCSM)
Y .Utsuno, Private communication

5. discussion 2 :
Comparison between experimental results and calculation
(1) Shell model calculation (USDB and SDPF-M)



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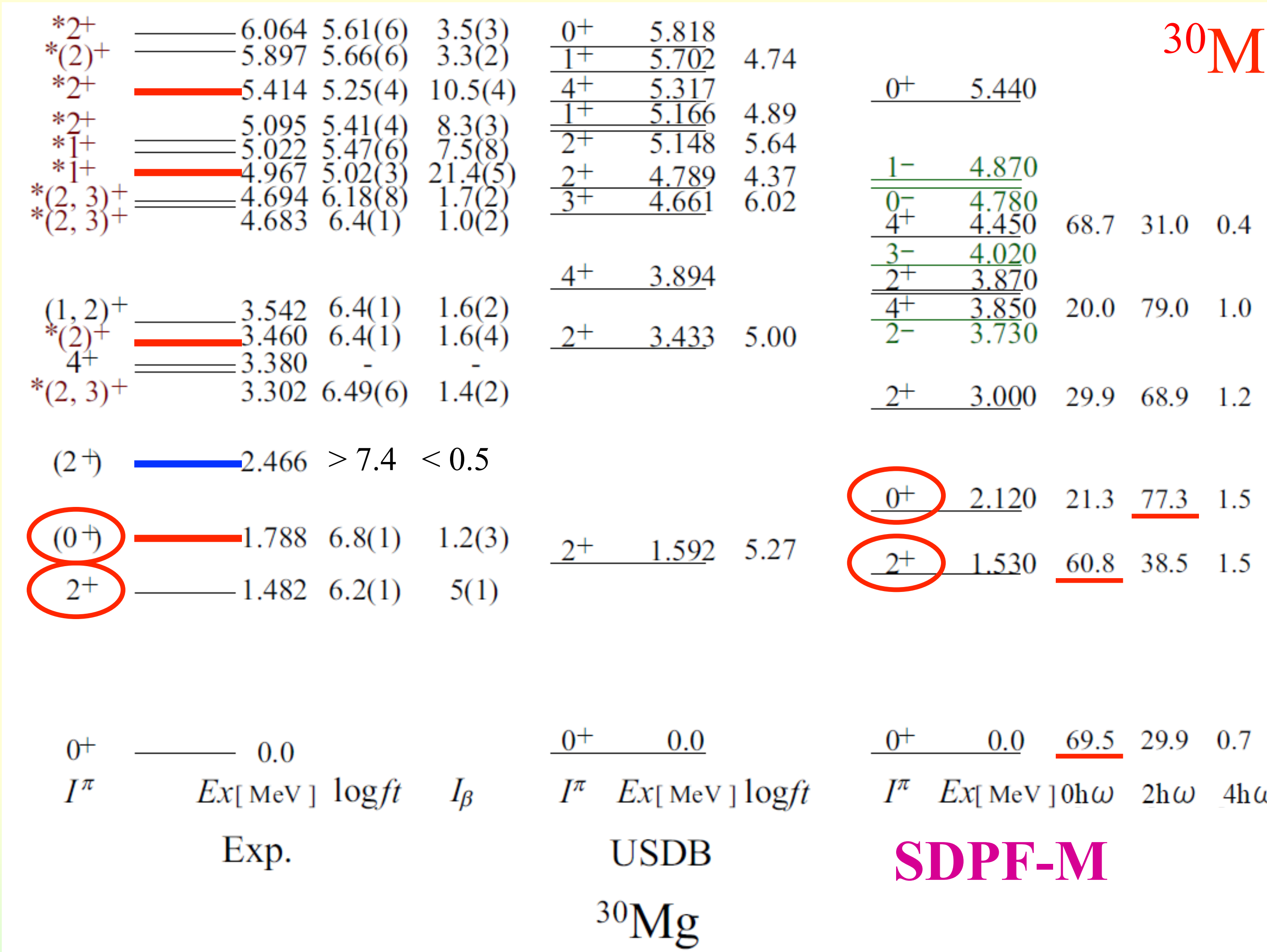

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Comparison between experimental results and calculation
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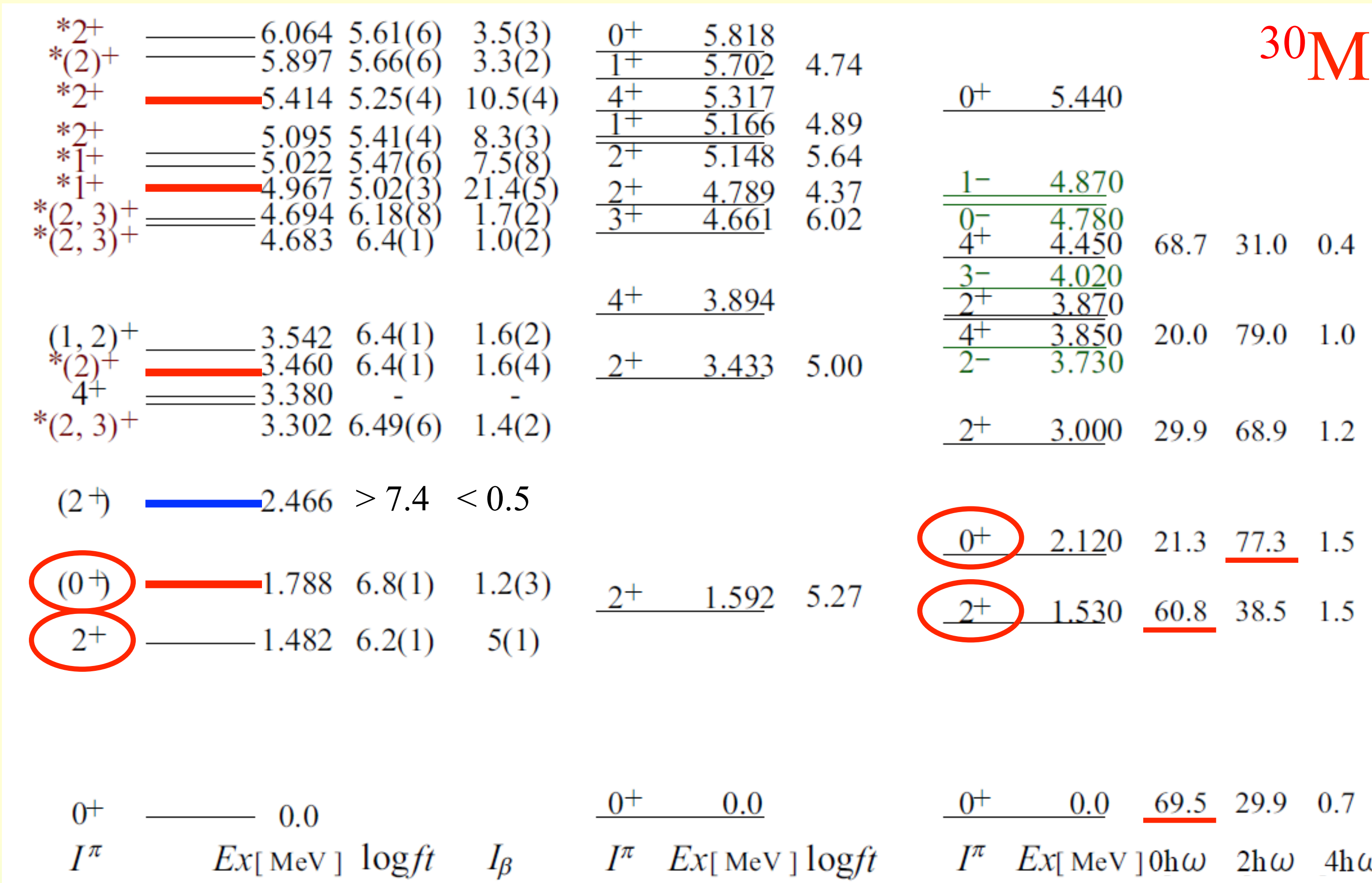
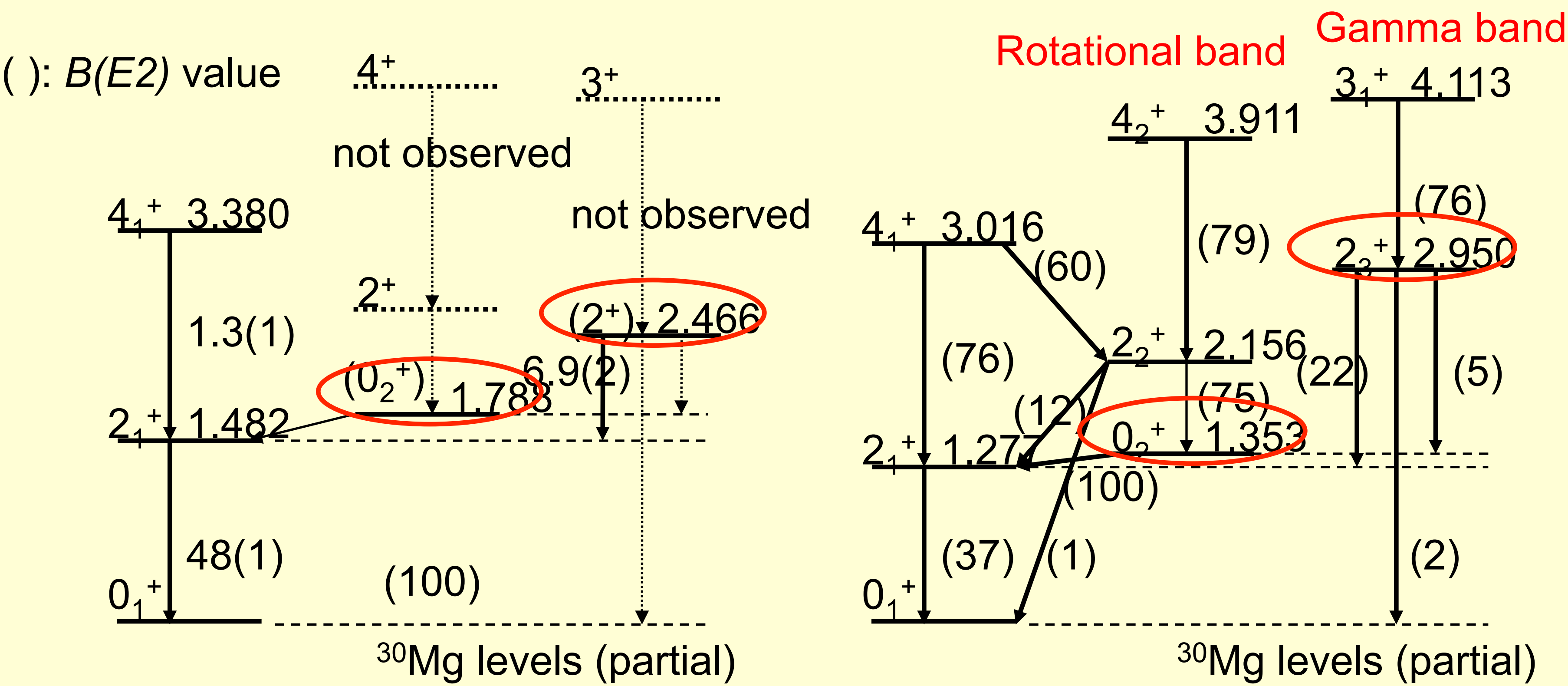


Good agreement can be seen for the levels at 1.482 MeV [2$^+$] [normal] and at 1.788 MeV [(0$^+$)] [intruder].

5. discussion 2 : Comparison between experimental results and calculation (2) Large amplitude collective motion (CHFB + LQRPA method)



[$E(4^+)/E(2^+)$ = 2.3]

Exp.

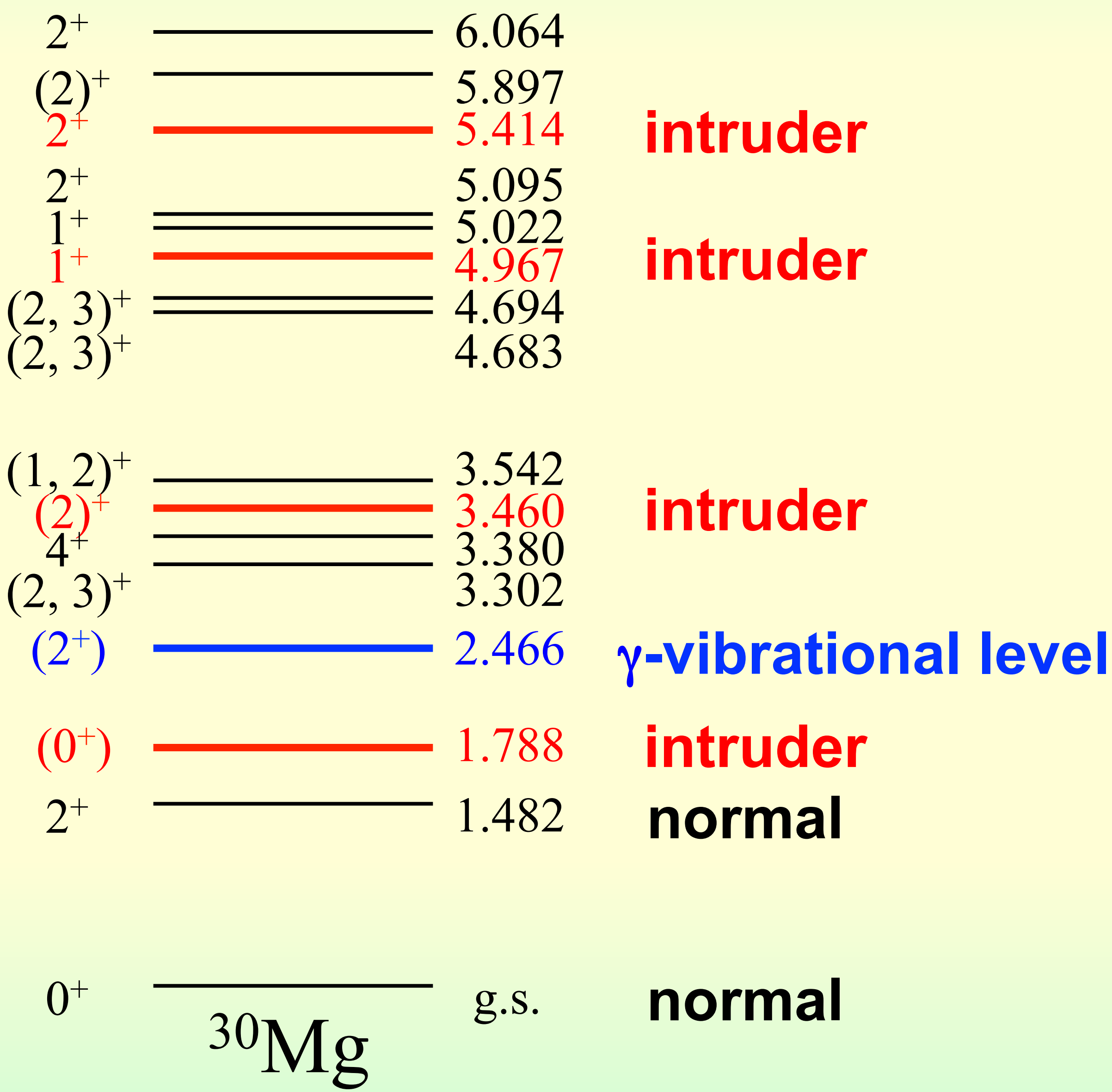
[$E(4^+)/E(2^+)$ = 2.4]

CHFB+LQRPA

N. Hinohara et al., Phys. Rev.C 84 (2011) 061302

Level at 2.466 MeV [(2^+)] : 2^+ in Gamma-band ?

Summary of the nuclear structure in ^{30}Mg



Summary

- We have successfully revised the level scheme of ^{30}**Mg** in β-decay spectroscopy of spin-polarized ^{30}Na.
- 4 levels and 14 γ-rays were newly observed.

  Spins and parities of 5 levels have been firmly assigned.

  Those of 5 other levels have been reasonably proposed.
- The observed β- and γ-transition paths and intensities strongly suggest that

  the four levels of

  (0^{+})(1.788 MeV), (2+)(3.460), 1^{+}(4.967), and 2^{+}(5.414)

  have large components of intruder configuration

  and one level of (2+) (2.466 MeV)

  is expected to be one of members in γ-band.

TRIUMF Experiment S1114

A. Odahara, K. Tajiri, T. Shimoda,
M. Suga, N. Hamatani, H. Nishibata,
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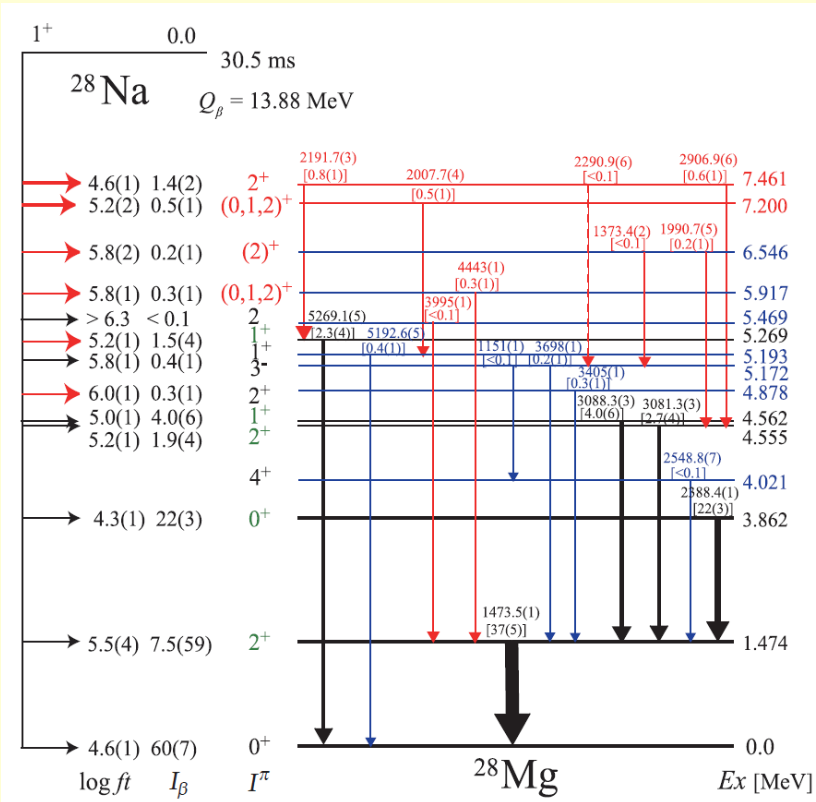
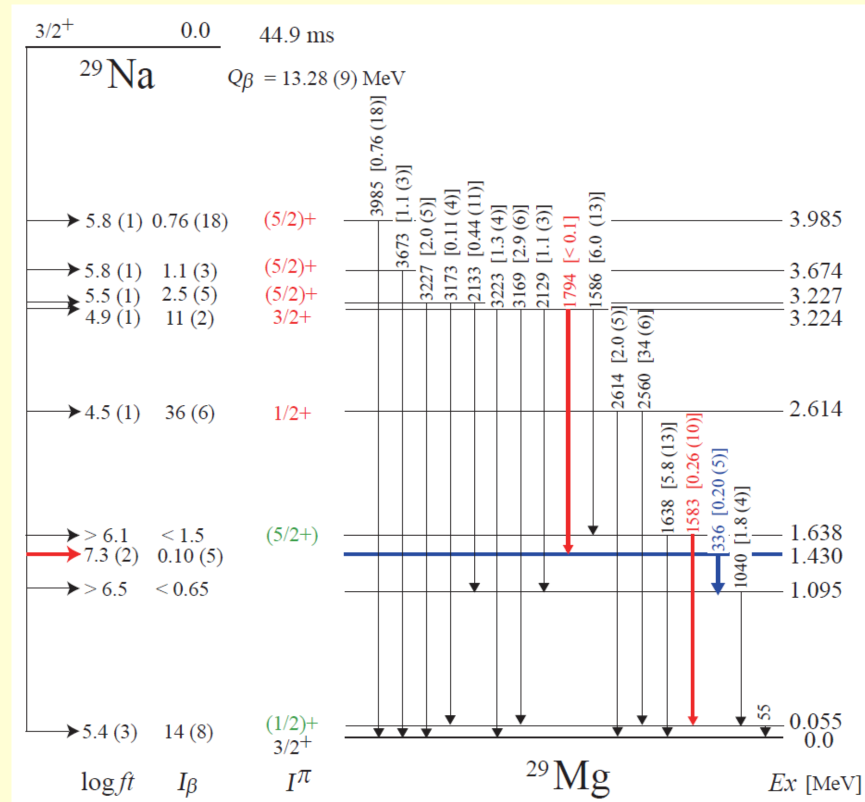
N. Imai[A], H. Miyaktake[A], M. Pearson[B],
C.D.P. Levy[B], K.P. Jackson[B],
R. Legillon[C] and C. Petrache[C]

Osaka Univ., KEK[A],TRIUMF[B],
Univ. Paris and IPN Orsay[C]

Thank you for your attention.

Revised Decay Scheme of ^{28,29}Na and New Levels in ^{28,29}Mg



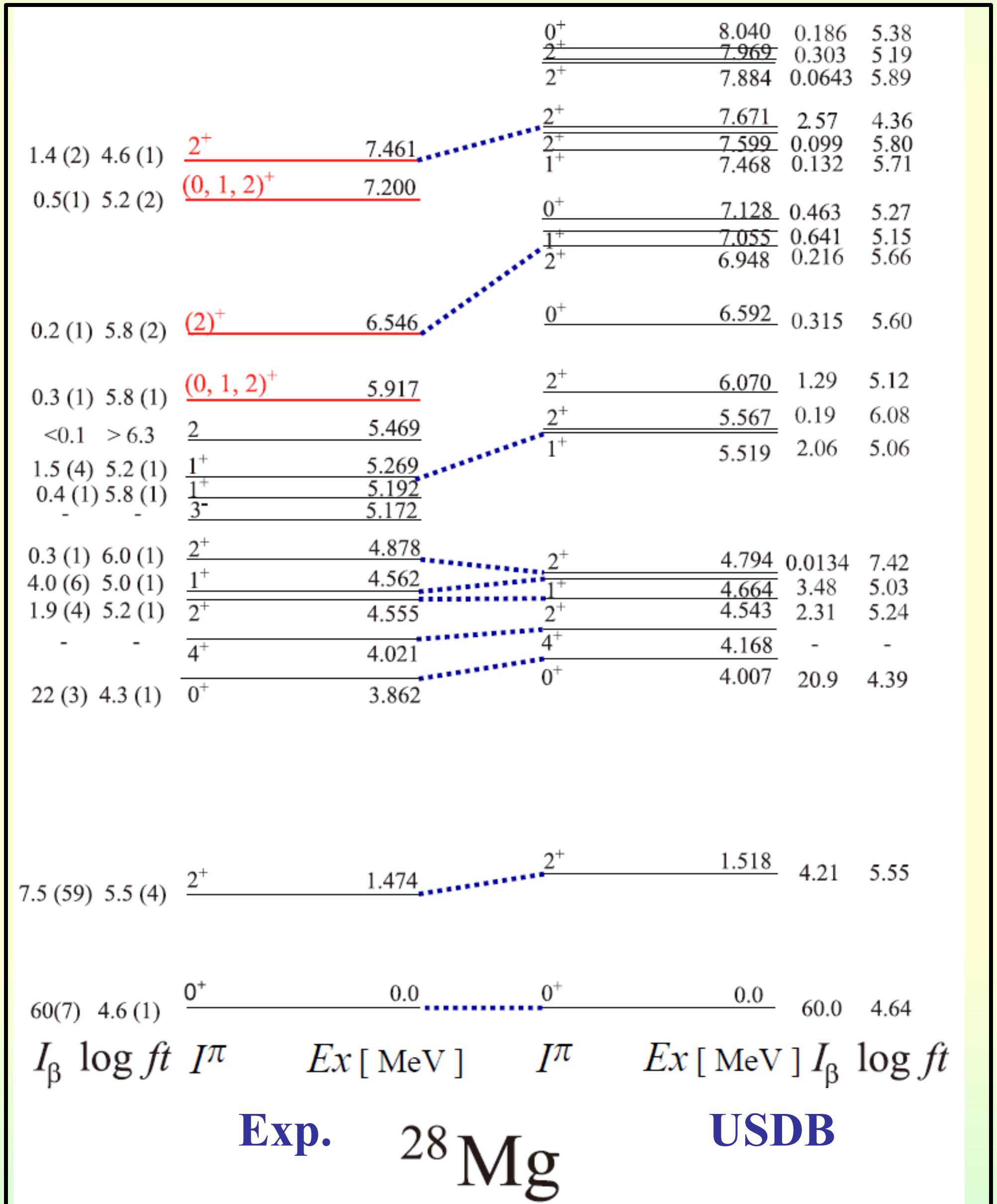


13 γ rays & 9 energy levels
Spins & parities of 4 levels

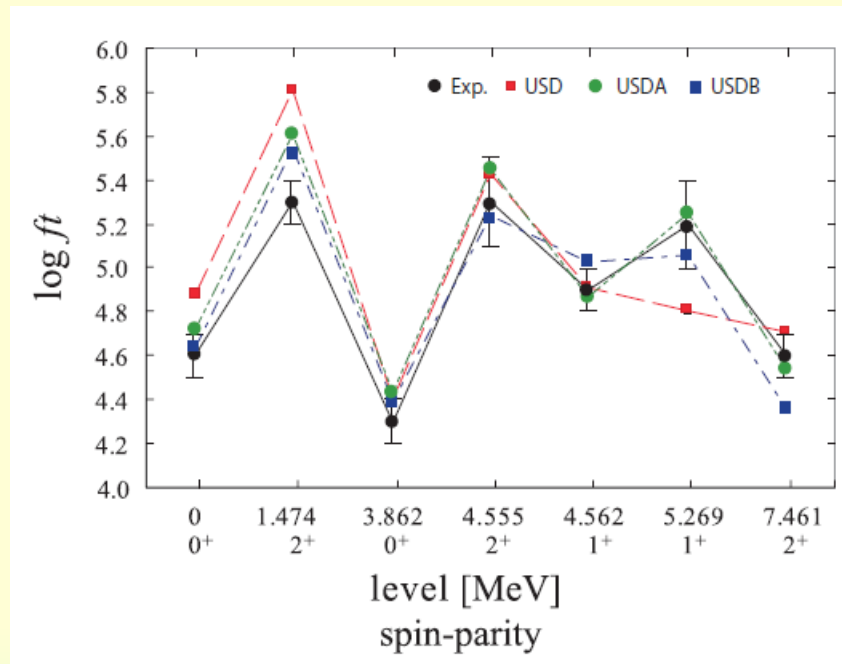
3 γ rays & 1 energy levels
Spins & parities of 7 levels

Comparison with Shell Model Calculation

^{28}Mg



interactions { USD, USDA, USDB }

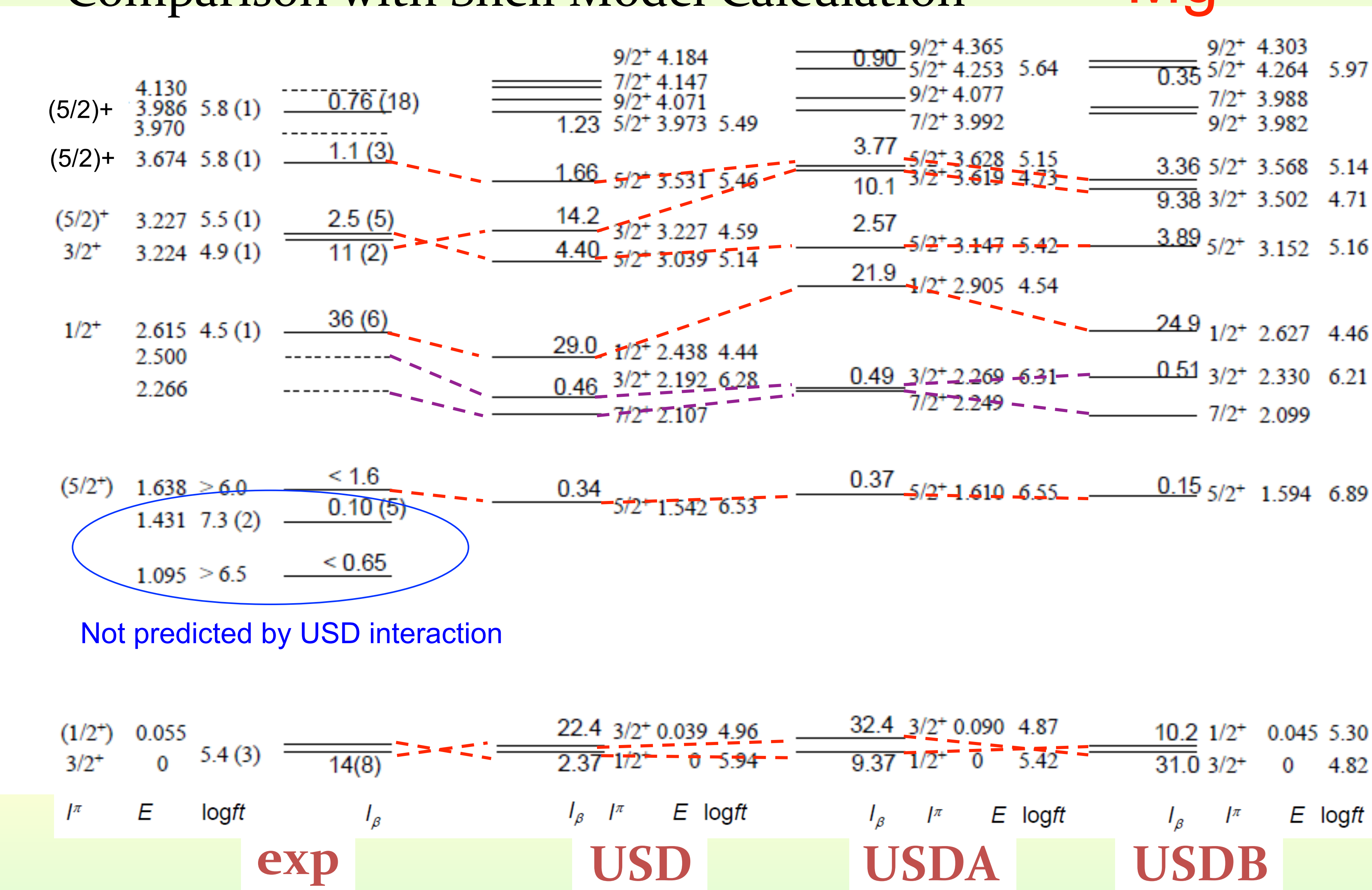


Code : NuShell

B.A. Brown et al., Phys. Rev. C74, 034315 (2006).

Comparison with Shell Model Calculation

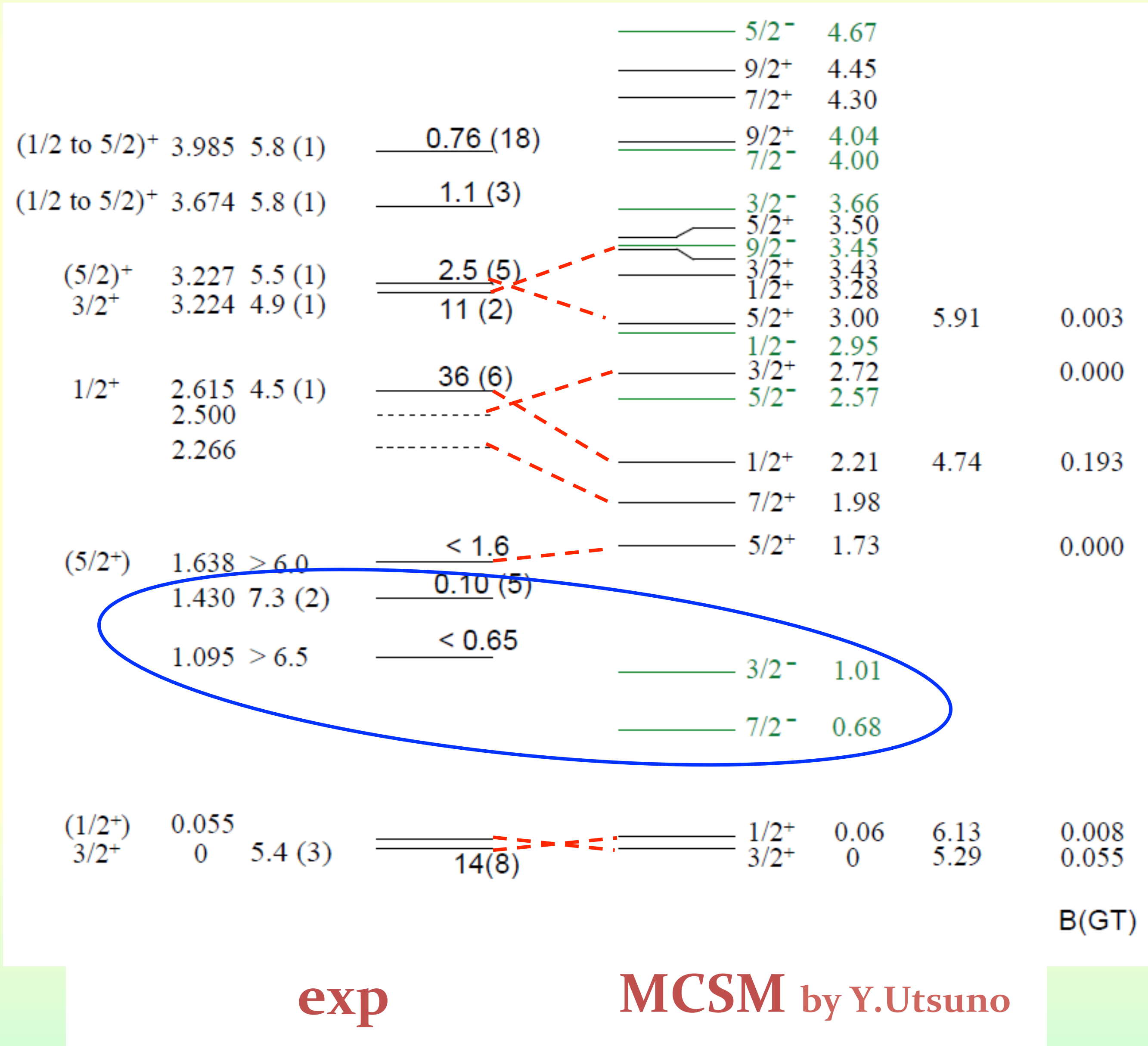
^{29}Mg



Code : NuShell

B.A. Brown et al., Phys. Rev. C74, 034315 (2006).

Comparison with Shell Model Calculation 2
(Monte Carlo Shell Model by Utsuno et al.)



Generalized Bohr-Mottelson collective Hamiltonian

recent review: Próchniak and Rohoziński, J. Phys. G **36** 123101 (2009)

$$\mathcal{H}_{\rm coll} = \boxed{V(\beta,\gamma)} + T_{\rm vib} + T_{\rm rot}$$

$$T_{\rm vib} = \frac{1}{2}\boxed{D_{\beta\beta}(\beta,\gamma)}\dot{\beta}^2 + \boxed{D_{\beta\gamma}(\beta,\gamma)}\dot{\beta}\dot{\gamma} + \frac{1}{2}\boxed{D_{\gamma\gamma}(\beta,\gamma)}\dot{\gamma}^2$$

$$T_{\rm rot} = \frac{1}{2}\sum_{k=1}^{3}\boxed{\mathcal{J}_k(\beta,\gamma)}\omega_k^2$$

V(β, γ)	collective potential
D(β, γ)	vibrational collective mass
J(β, γ)	rotational moment of inertia

Microscopic derivations of functions in collective Hamiltonian

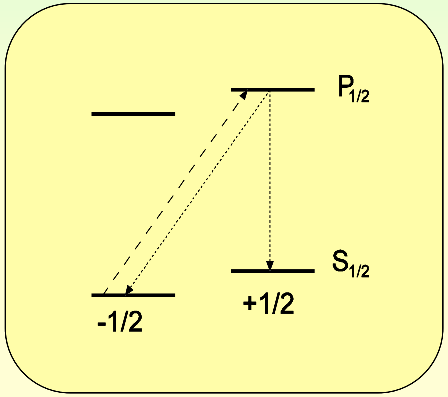
CHFB+LQRPA method NH et al., Phys. Rev. C**82**, 064313 (2010)

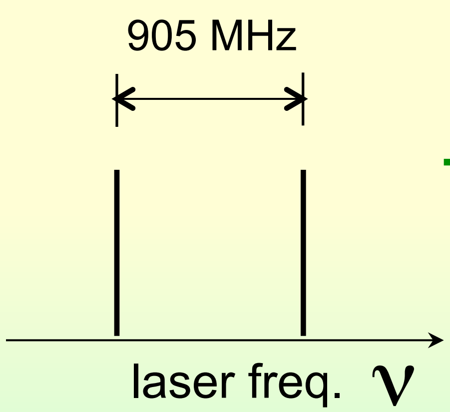
Constrained Hartree-Fock-Bogoliubov equation	⇨ **V(β, γ)**
Local QRPA equations for vibration	⇨ **D(β, γ)**
Local QRPA equations for rotation	⇨ **J(β, γ)**

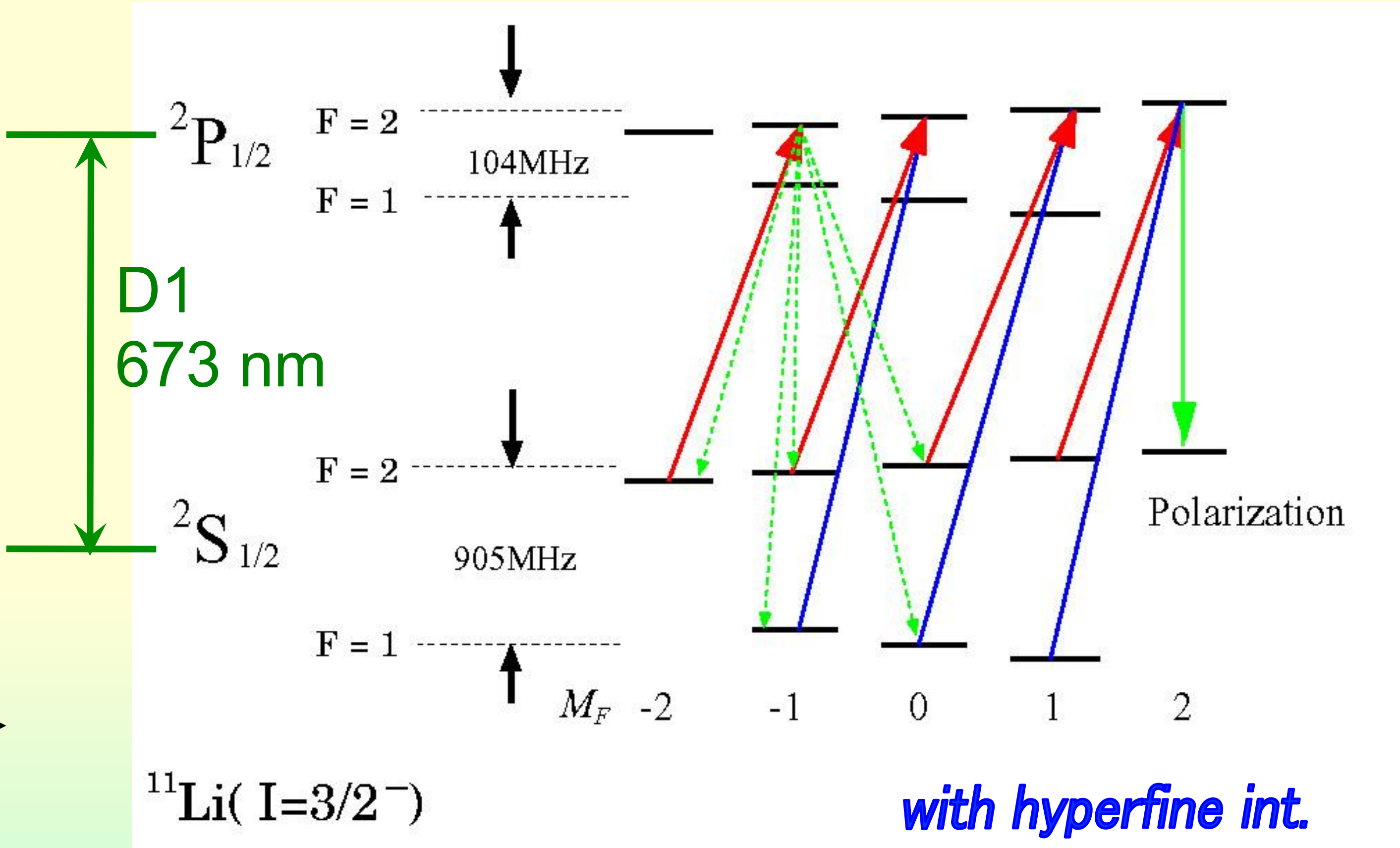
- QRPA on top of CHFB state
- solved at each point in (β,γ) plane
- Hamiltonian used in QRPA also contains constraint terms
- derived from adiabatic self-consistent collective coordinate method
  (a successful version of ATDHFB theory) Matsuo et al., Prog.Theor.Phys.**103**,959 (2000)

pumping the two ground-state hyperfine levels in order to achieve high polarization

without hyperfine int.







Polarized beam line at TRIUMF

Commissioned in 2001

Two hyperfine levels are pumped
Matching with the broad absorption line width

polarization achieved so far

^{8}Li: 80%, ^{9}Li: 56%, ^{11}LI: 55%,

^{20}Na: 57%, ^{21}Na: 56%, ^{26}Na: 55%,
^{27}Na: 51%, ^{28}Na: 45%

Pumping for $^{11}Be^{+}$ beam is in progress.

Alkali RI beam from ISOL

A^{+1} beam at 10 – 60 keV

↓

neutralizer

charge exchange in a Na vapor jet

$A^{+1} + Na \rightarrow A^{0} + Na^{+1}$: 90% efficiency

↓

optical pumping

for fast neutral beam in collinear geometry

two laser beams to pump the two ground-state hyperfine levels

longitudinal polarization

↓

re-ionizer

collision with a cold He gas target (12K)

$A^{0} \rightarrow A^{+1}$: 66% efficiency

bend ⇨ transversely nuclear-polarized ion beam

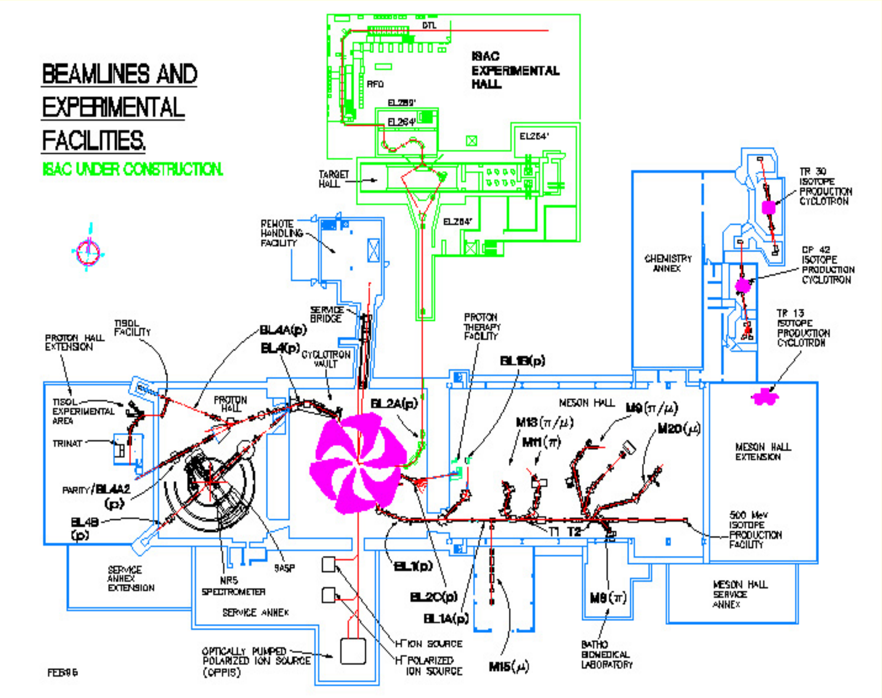
TRIUMF ISAC

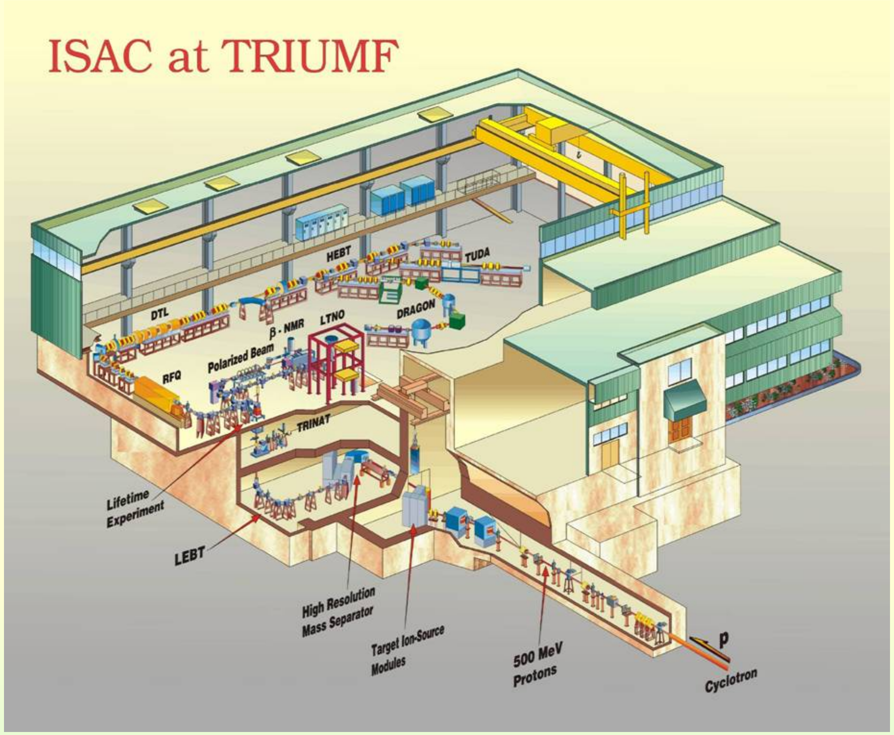
Isotope Separator / ACcelerator

radioactive nuclear beams produced by 500 MeV 100 μA proton beam

ISAC-I: A ≦30, 1.5 MeV/u (construction: 1995 - 2000)
ISAC-II: A ≦150, 6.5 MeV/u (construction: 2000 - 2005)

ISAC-I





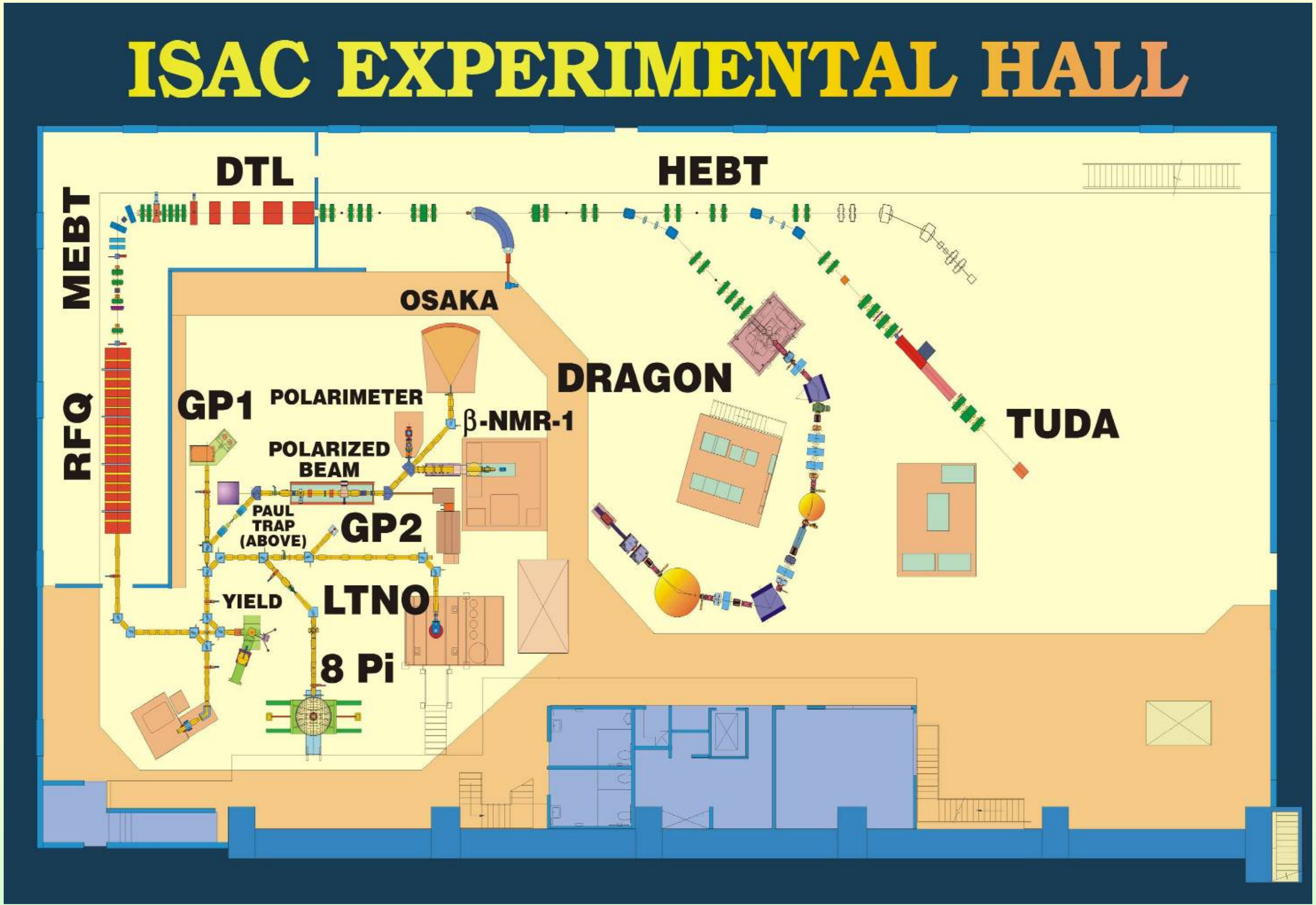
H⁻acceleration, extraction to 3 ports simultaneously
In operation since 1974

TRIUMF ISAC-I Experimental Hall

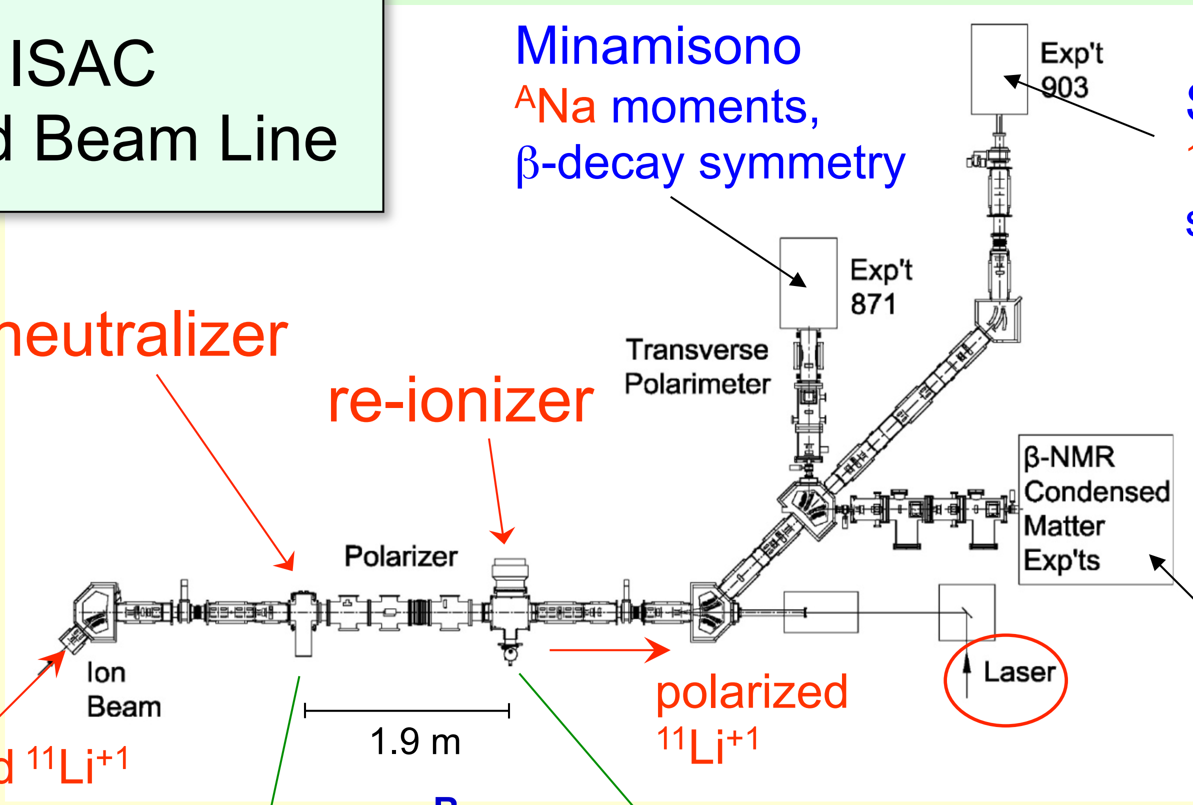
low energy beam line: Polarized beam, Osaka, β-NMR, LTNO (Low Temperature Nuclear Orientation), 8Pi (Gamma ball), GP (General Purpose)

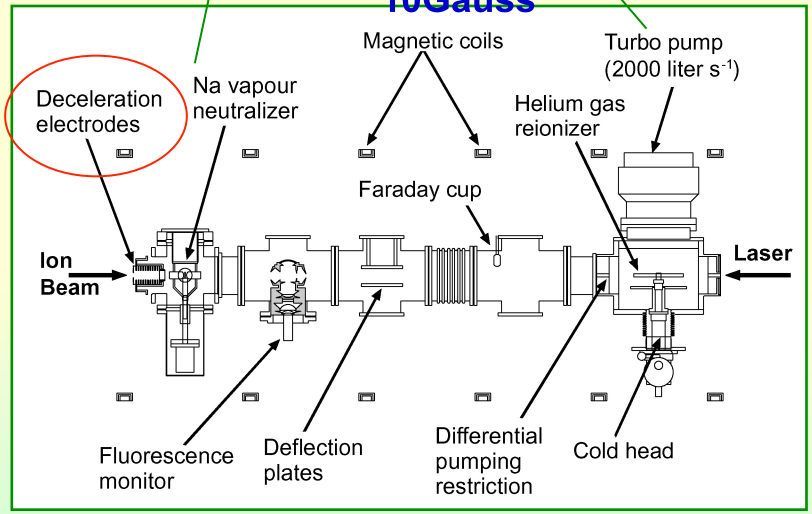
high energy beam line: DRAGON (nuclear astrophysics), TUDA (TRIUMF-U.K. Detector Array)

under ground level: TRINAT (TRIUMF Neutral Atom Trap), Lasers for polarized beam line



TRIUMF ISAC Polarized Beam Line





pumping within 2.6μs

C.D.P. Levy et al.
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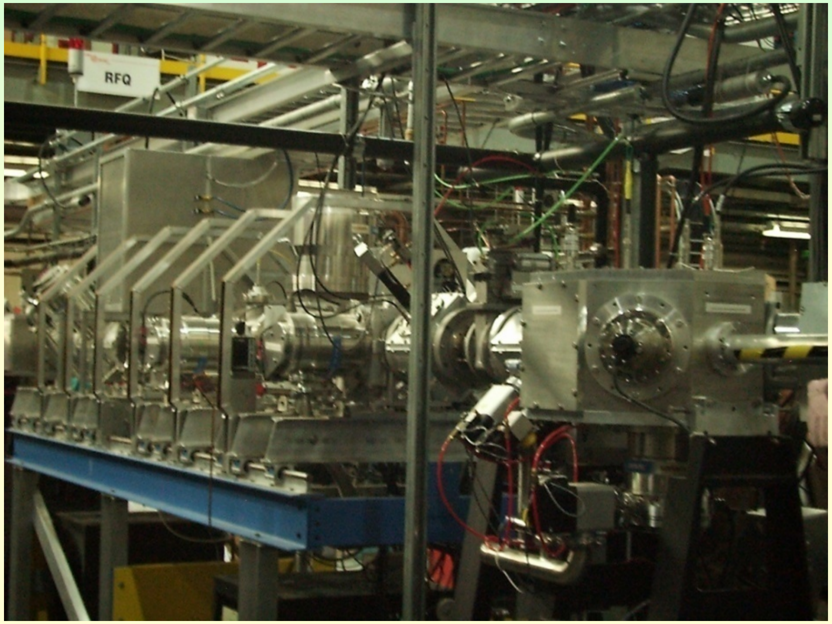
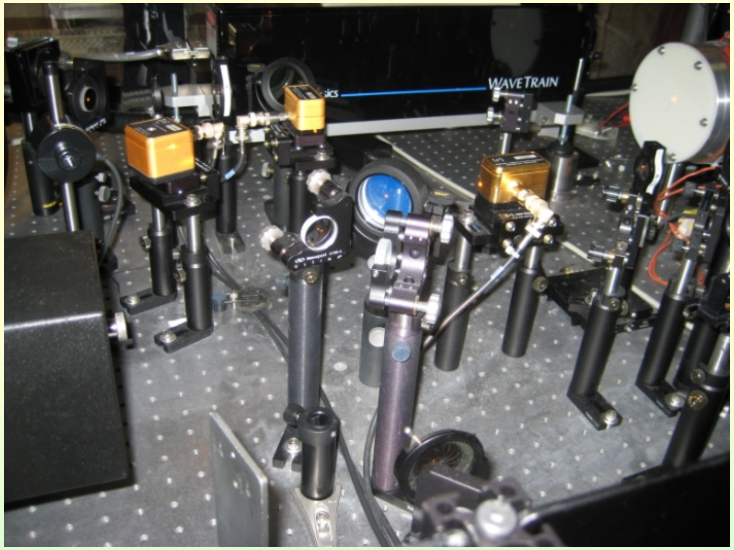
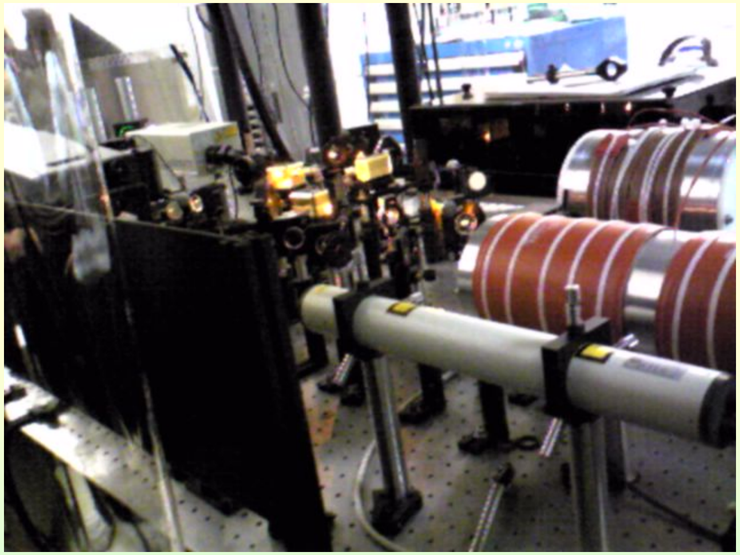
Polarized beam line



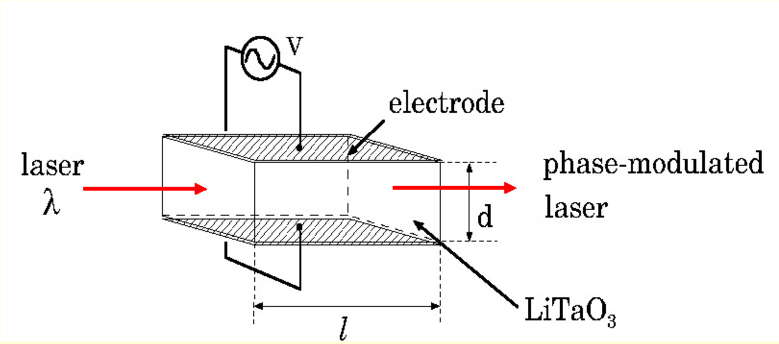
laser system

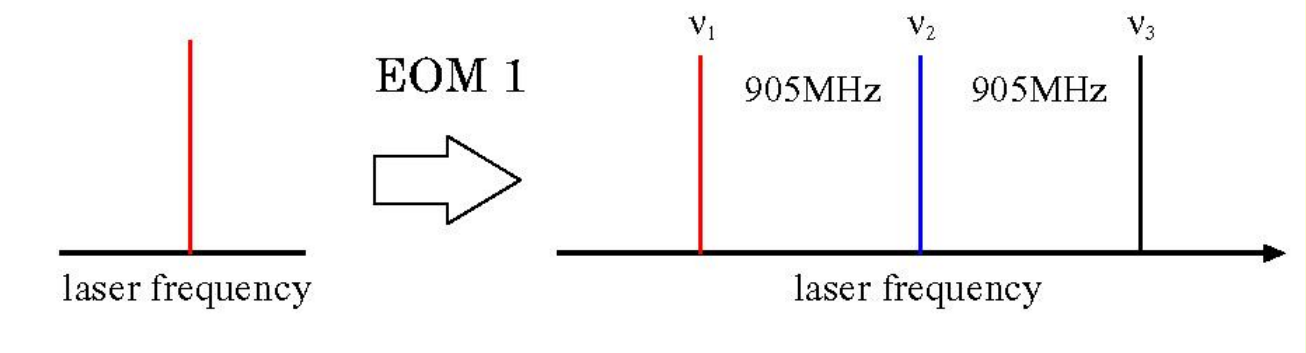




Electro-Optic Modulator (EOM)

driven at the hyperfine splitting frequency



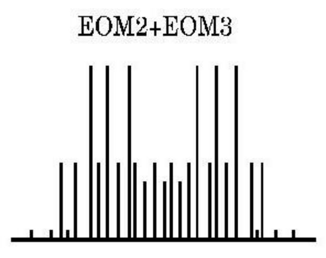


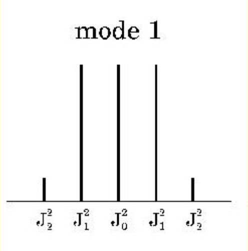
Only 1/3 laser power is used for each optical pumping.

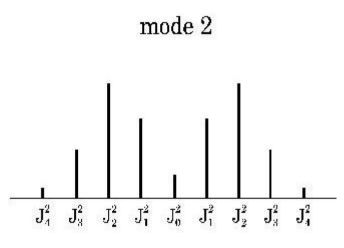
broadening the laser line width

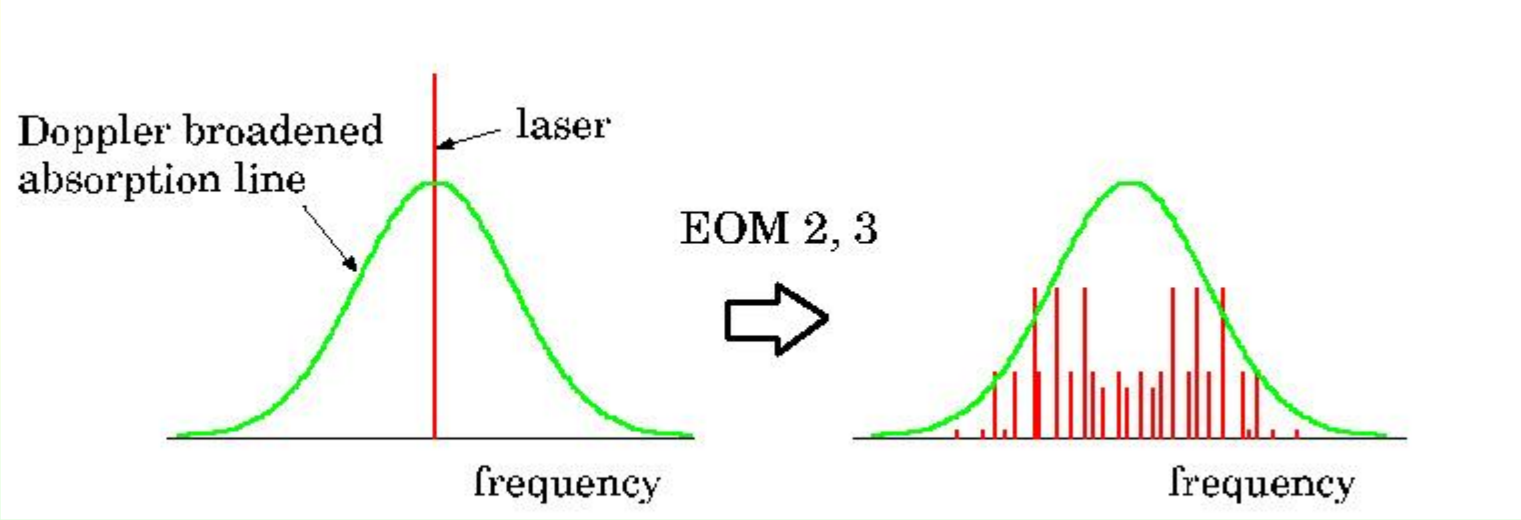
two EOMs in series

laser beam → EOM-2 19 MHz → EOM-3 28 MHz →









^{8}Li

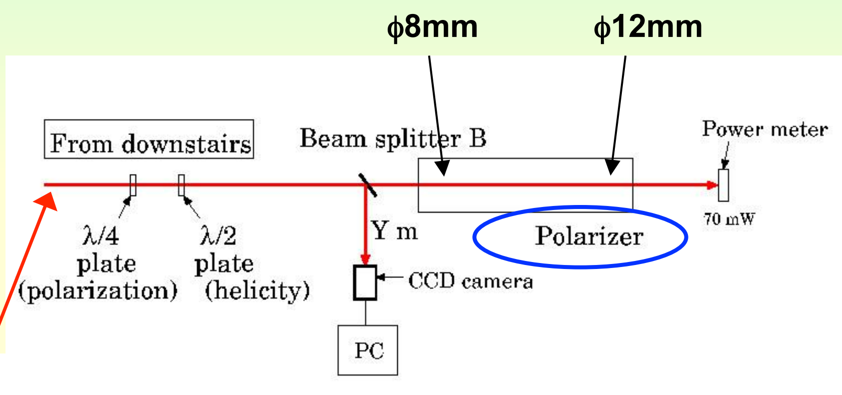
P～20%

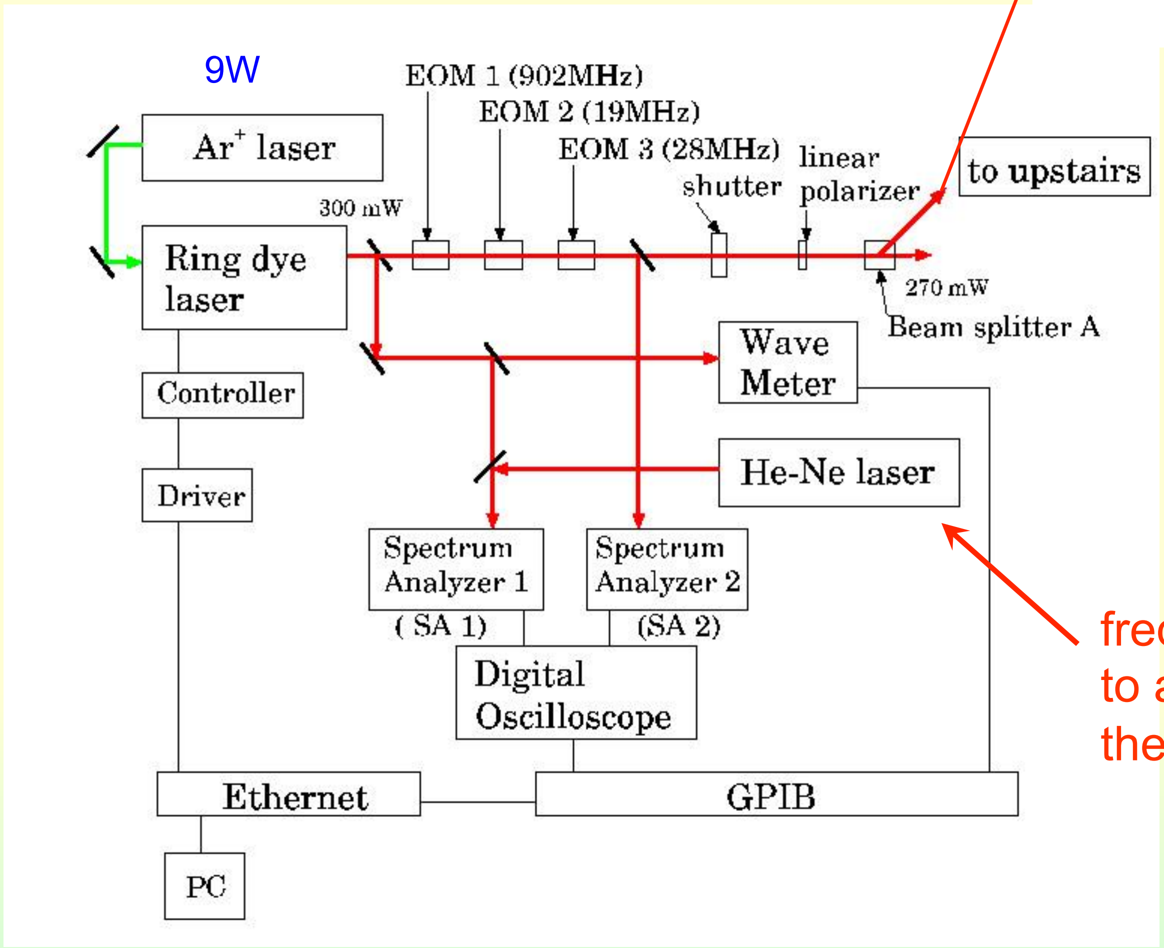
⇩

P～70%

Laser system

Ring dye laser
Coherent 899-21
Dye: DCM SPECIAL/LC 6501





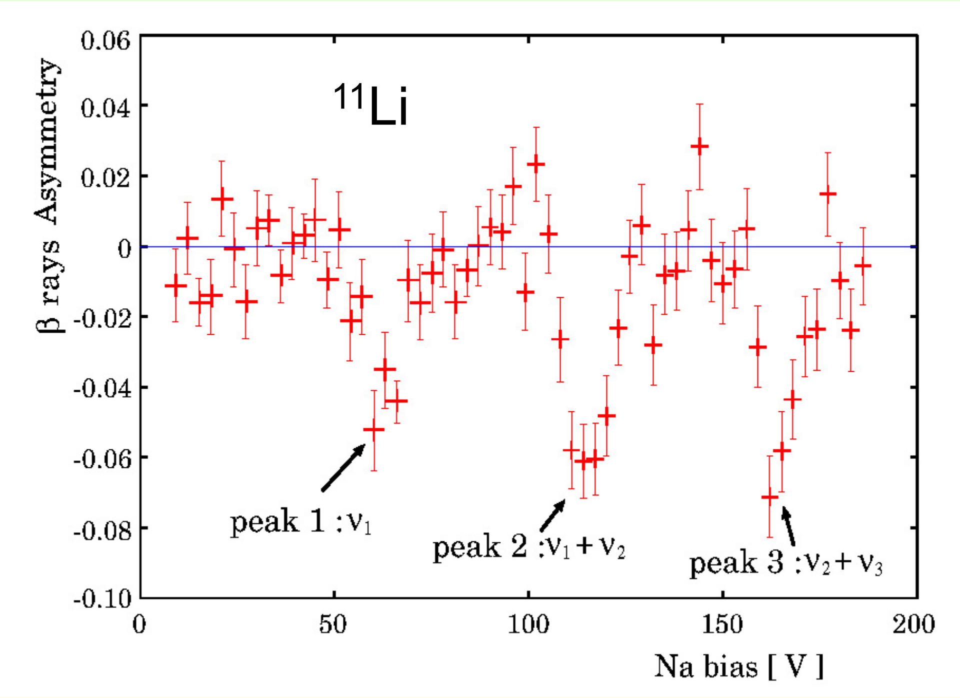
673 nm cw
circular polarized
for ^{11}Li

frequency reference
to actively stabilize
the ring dye laser

Doppler-shift tuning

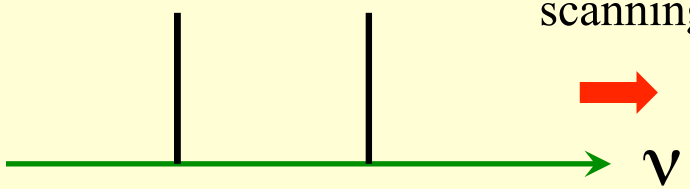
deceleration bias (Na vapor cell)
tuning to adjust ion beam velocity
so as to meet the Doppler shift

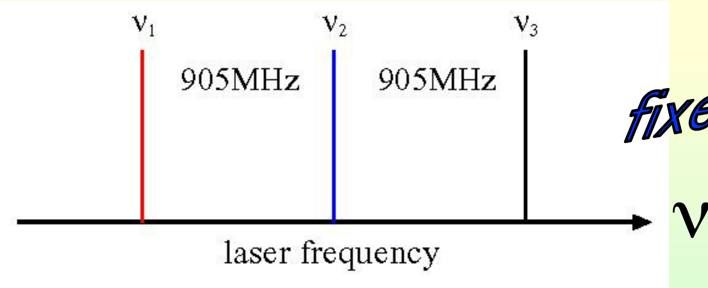
beta-decay asymmetry



absorption line

scanning velocity

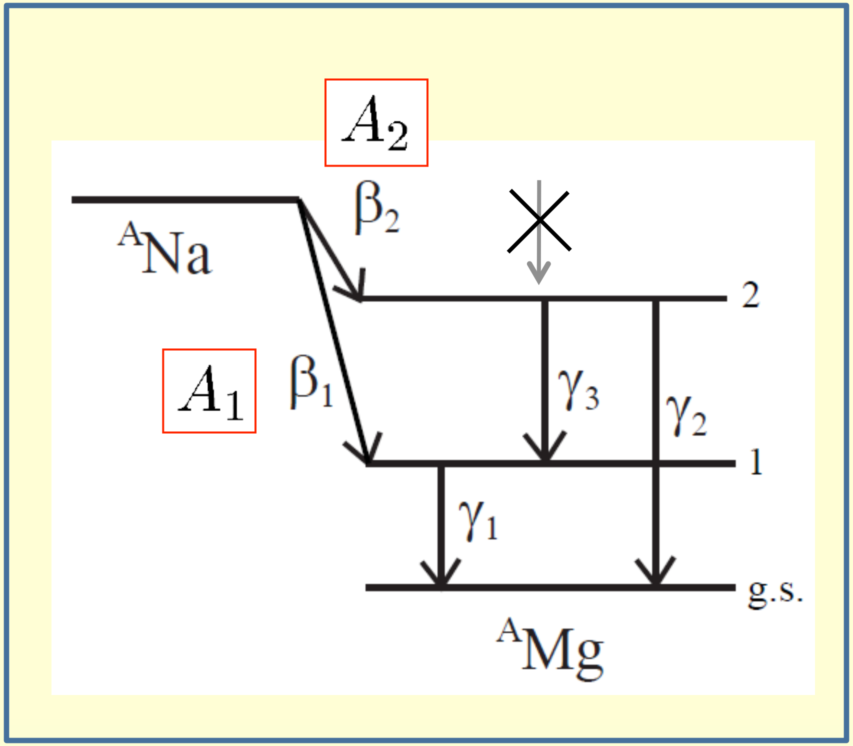




fixed

In the case of cascade feeding

Deduced A from β-γ coincidence is affected by the feeding from upper levels.



measured from β-γ_1 coincidence

$$A_1^{\gamma} = A_2 \times \frac{I_{\gamma_3}}{I_{\gamma_1}} + A_1 \times \frac{I_{\beta_1}}{I_{\gamma_1}},$$

known unknown

$$A_1 = A_1^{\gamma} \times \frac{I_{\gamma_1}}{I_{\beta_1}} - A_2 \times \frac{I_{\gamma_3}}{I_{\beta_1}}.$$